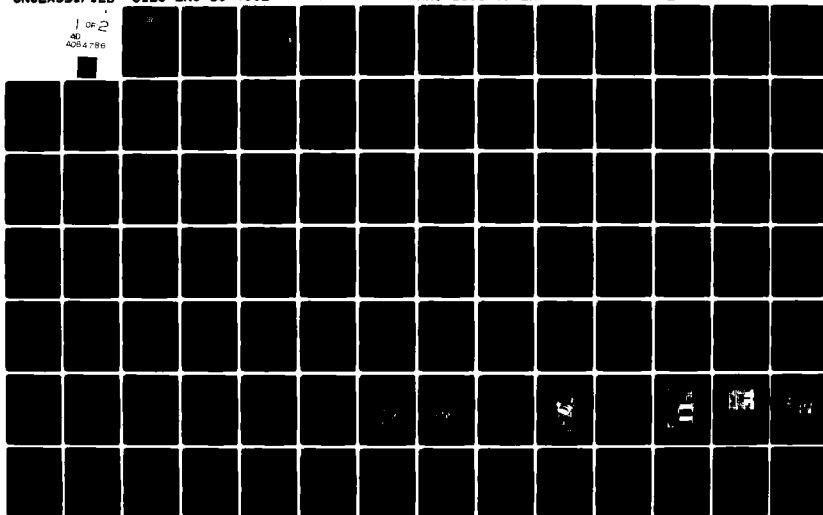


AD-A084 786

ILLINOIS UNIV AT URBANA-CHAMPAIGN DEPT OF MECHANICAL --ETC F/G 20/4  
AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF MULTIPLE DUCTE--ETC(U)  
JAN 80 H L PETRIE, A L ADDY DAAG29-76-6-0200  
UILL-ENG-80-4002 ARO-13737.2-EX ML

UNCLASSIFIED

1 OF 2  
40  
AD84786



ARO 13737.2-EX

MECHANICAL ENGINEERING LABORATORY  
UIIU-ENG-80-4002  
DEPARTMENT OF MECHANICAL  
AND INDUSTRIAL ENGINEERING  
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN  
URBANA, ILLINOIS 61801



LEVEL

FINAL TECHNICAL REPORT

**AN EXPERIMENTAL AND THEORETICAL INVESTIGATION  
OF MULTIPLE DUCTED STREAMS WITH A PERIODIC  
OR A STEADY SUPERSONIC DRIVER FLOW**

by  
H. L. PETRIE  
A. L. ADDY

DTIC  
ELECTE  
MAY 28 1980

JANUARY 1980

AD A 084786

DDC FILE COPY

Supported by  
U.S. Army Research Office  
Research Grant DAAG 29-76-G-0200  
and the  
Department of Mechanical and Industrial Engineering

Approved for Public Release; Distribution Unlimited

80 5 27 222

*Errata*  
to Report  
"An Experimental and Theoretical Investigation  
of Multiple Ducted Streams with a Periodic  
or a Steady Supersonic Driver Flow"

On page 25, change the last two lines on the page from

"Section 6.0, the APPENDIX, contains ..."

to

"APPENDIX A, contains ..."

On page 144, change the second and third lines from the bottom from

"... to drive a supersonic-subsonic configuration during ..."

to

"... to drive a supersonic-subsonic ejector configuration during ..."

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER UILU-ENG-80-4002	2. GOVT ACCESSION NO. AD-A084 786	3. RECIPIENT'S CATALOG NUMBER ----
4. TITLE (and Subtitle) An Experimental and Theoretical Investigation of Multiple Ducted Streams with a Periodic or a Steady Supersonic Driver Flow		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 1976-80
7. AUTHOR(s) H. L. Petrie, A. L. Addy		6. PERFORMING ORG. REPORT NUMBER UILU-ENG-80-4002
9. PERFORMING ORGANIZATION NAME AND ADDRESS Dept. of Mechanical and Industrial Engineering/ University of Illinois at Urbana-Champaign Urbana, Illinois 61801		8. CONTRACT OR GRANT NUMBER(s) DAAG 29-76-G-0200
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 13 1732
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 1) Final Rept. 116-1790,		12. REPORT DATE Jan 1980
		13. NUMBER OF PAGES 160
		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) 18) AFD 19) 13734.2-EX		
18. SUPPLEMENTARY NOTES The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Supersonic Ejector      Periodic Flow Mixing Flows Steady Flow		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An experimental and theoretical investigation of a supersonic-subsonic, two-dimensional planar, constant area ejector with a periodically pulsed or a steady driver flow is discussed. A large scale fluidic oscillator was developed to partially pulse the driver flow at frequencies up to 250 Hz. A wide range of ejector flow conditions were experimentally investigated with three values of ejector mixing duct length-to-width ratios. Driver flow frequencies of 142 Hz and 250 Hz were used in the ejector experiments and a		

DTIC  
ELECTE  
MAY 28 1980

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

complete set of steady driver flow experiments was conducted. A one-dimensional, quasi-steady control volume analysis was successfully employed to model these ejector flows.

Unsteady ejector flows were found to be modeled well by the quasi-steady analysis. Both steady and unsteady ejector flow performance parameters were accurately predicted by the one-dimensional analysis with the exception of the pressure recovery characteristics observed. Experimentally determined compression ratios were about 25% lower than predicted by the analysis. The pulsation of the driver flow was found to have little effect on ejector operation. Mixing and entrainment characteristics did not appear to be altered by the pulsed driver. Pressure recovery was enhanced but only slightly. The steady driver ejector flows were quite unexpectedly found to be unstable and highly disturbed under most flow conditions. It was felt this may have negated the effects of the pulsed driver flow. The Strouhal number of pulsed driver flows was not felt to be high enough to significantly effect the dynamics of mixing between high speed ducted streams.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DEC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
A	

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

AN EXPERIMENTAL AND THEORETICAL INVESTIGATION  
OF MULTIPLE DUCTED STREAMS WITH A PERIODIC  
OR A STEADY SUPERSONIC DRIVER FLOW\*

by

H. L. Petrie<sup>†</sup>

A. L. Addy<sup>††</sup>

January 1980

Supported by

U.S. Army Research Office  
Research Grant DAAG 29-76-G-0200

and the

Department of Mechanical and Industrial Engineering  
University of Illinois at Urbana-Champaign  
Urbana, Illinois 61801

Approved for Public Release; Distribution Unlimited

---

\* This report is based on the M.S. thesis of H. L. Petrie

<sup>†</sup> Graduate Research Assistant

<sup>††</sup> Professor of Mechanical Engineering

## ACKNOWLEDGMENTS

We wish to acknowledge the support provided for this research by the U.S. Army Research Office under grant number DAAG 29-76-G-0200.

Mr. James J. Murray of the U.S. Army Research Office served as the Technical Monitor of this grant.

## TABLE OF CONTENTS

	Page
NOMENCLATURE .....	ix
LIST OF FIGURES .....	xi
1.0 INTRODUCTION .....	1
1.1 STATEMENT OF THE PROBLEM .....	1
1.2 GENERAL BACKGROUND AND LITERATURE SURVEY .....	3
2.0 THEORETICAL ANALYSIS OF THE CONSTANT AREA SUPERSONIC-SUBSONIC EJECTOR WITH A PERIODIC DRIVER FLOW .....	11
2.1 EJECTOR FLOW REGIMES .....	11
2.2 OVERALL CONTROL VOLUME ANALYSIS .....	15
2.3 SUPERSONIC REGIME ANALYSIS .....	21
2.4 COMPUTATIONAL PROCEDURE .....	24
2.5 PARAMETRIC STUDY .....	26
3.0 THE EXPERIMENTAL PROGRAM .....	35
3.1 EXPERIMENTAL APPARATUS .....	35
3.2 EXPERIMENTAL PROCEDURE .....	43
3.2.1 Steady Flow Experimental Procedure .....	44
3.2.2 Periodic Flow Experimental Procedure .....	46
3.3 EXPERIMENTAL RESULTS .....	48
3.3.1 Steady Flow Experimental Results .....	48
3.3.2 Periodic Flow Experimental Results .....	51
4.0 CONCLUSIONS .....	113
5.0 REFERENCES .....	119
APPENDIX A .....	123
A.1 UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE) .....	125
A.2 SAMPLE INPUT AND OUTPUT .....	139
APPENDIX B .....	141
B.1 WATER TABLE EXPERIMENTS .....	141
B.2 AIR FLOW FLUIDIC OSCILLATOR EXPERIMENTS .....	147
APPENDIX C .....	159

## NOMENCLATURE

Symbols

A	Area.
$C_p$	Specific heat at constant pressure.
$C_v$	Specific heat at constant volume.
d	Jet diameter.
$f_1( )$ , $f_2( )$ , ...	Gas dynamic functions defined in the text.
F	Force.
g	The acceleration due to gravity.
h	Specific enthalpy.
L	Mixing duct length.
M	Mach number.
Mw	Molecular weight.
P	Pressure.
Q	Heat.
R	Universal gas constant.
St	Strouhal number.
t	Time.
T	Absolute temperature.
V	Magnitude of velocity.
w	Mass flowrate.
$w_{sp}$	Secondary to primary mass flowrate ratio.
W	Mixing duct width.
$w_{ss}$	Work, shaft and shear.
X	Longitudinal or flow-direction coordinate.

Symbols (cont.)

Z	Elevation.
$\gamma$	Ratio of specific heats.
$\rho$	Density.
$\omega$	Frequency.

Subscripts

o	Stagnation state.
1,2,3	System locations.
cs	Control surface.
m	Mixed.
p	Primary flow.
s	Secondary flow.
x	Quantity in the flow coordinate direction.

Superscripts

*	Choked flow quantity.
—	Mean value.

Acronyms

APPR	Approximate flow regime.
MR	Mixed flow regime.
SR	Supersonic flow regime.
SSR	Saturated supersonic flow regime.
UCAE	Unsteady constant area ejector program.

## LIST OF FIGURES

Figure		Page
2.0-1	Control volume used in the overall analysis .....	28
2.1-1	Control volume used in the supersonic regime analysis .	29
2.1-2	The one-dimensional inviscid analysis solution surfaces	30
2.5-1	Theoretical mass flowrate characteristics of the back pressure independent flow regimes versus $P_{s0}/P_{p0}$ .....	31
2.5-2	Theoretical characteristics of $P_{s1}/P_{p1}$ for the back pressure independent flow regimes versus $P_{s0}/P_{p0}$ .....	32
2.5-3	Theoretical values of $M_{s1}$ for the back pressure independent flow regimes versus $P_{s0}/P_{p0}$ .....	33
2.5-4	Theoretical values of $P_{ins}/P_{s0}$ at which SR, APPR, and SSR flows break-off to MR flow versus $P_{s0}/P_{p0}$ .....	34
3.1-1	Flow schematic of the test rig .....	61
3.1-2	The fully assembled ejector unit ( $L/W = 9.0$ ) .....	62
3.1-3	The partially assembled ejector unit ( $L/W = 9.0$ ) .....	63
3.1-4	View of the partially assembled oscillator body .....	64
3.1-5	View of the primary flow inlet to the ejector .....	65
3.1-6	View of the partially assembled ejector base piece ....	66
3.1-7	View of the ejector mixing duct assemblies .....	67
3.1-8	View of the secondary and primary lines connected to the base assembly .....	68
3.1-9	View of the test rig .....	69
3.1-10	Cross-sectional view of the Scanivalve "zero" volume line adapter with a CEC type 4-312 pressure transducer in place .....	70
3.1-11	Schematic detailing the data acquisition system .....	71
3.3.1-1	Back pressure independent steady flow values of $P_{s1}/P_{p1}$ versus $P_{s0}/P_{p0}$ .....	72

Figure		Page
3.3.1-2	Back pressure independent steady flow values of $w_s/w_p$ versus $P_{s0}/P_{p0}$ .....	73
3.3.1-3	Steady flow values of the back pressure ratio above which SR flow breaks-off to MR flow versus $P_{s0}/P_{p0}$ ....	74
3.3.1-4	Steady flow static pressure distributions in the $L/W = 16.374$ mixing duct at $P_{m3}/P_{s0} = 2.45$ and $P_{1.3}/P_{s0} = 2.56$ ( $P_{s0}/P_{p0} \approx .078$ ) .....	75
3.3.2-1	Large amplitude pulses were observed in the subsonic wall flow of both steady and periodic driver experiments ( $P_{s0}/P_{p0} \approx .070$ ) .....	76
3.3.2-2	Wall flow static pressures were found to be symmetric about the primary flow centerline ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .....	77
3.3.2-3	Primary and secondary static pressures at Station 1 for the 142 Hz driver ejector flow versus time ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .....	78
3.3.2-4	Primary and secondary static pressures at Station 1 for the 250 Hz driver ejector flow versus time ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .....	79
3.3.2-5	Small disturbances in the subsonic wall flow of the steady driver ejector flow ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	80
3.3.2-6	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = .333$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	81
3.3.2-7	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = .333$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	82
3.3.2-8	Static pressures versus time in the steady driver ejector flow at $X/W = 1.00$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	83
3.3.2-9	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = 1.00$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	84
3.3.2-10	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = 1.00$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .	85
3.3.2-11	Static pressure pulses in a highly expanded shock free flow. $P_{m3}/P_{s0}$ is relatively low ( $L/W = 13.0$ , $P_{s0}/P_{p0} \approx .070$ ) .....	86

Figure		Page
3.3.2-12	Static pressures versus time in the steady driver ejector flow at $X/W = 1.333$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	87
3.3.2-13	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = 1.333$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	88
3.3.2-14	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = 1.333$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	89
3.3.2-15	Static pressures versus time in the steady driver ejector flow at $X/W = 4.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	90
3.3.2-16	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = 4.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	91
3.3.2-17	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = 4.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	92
3.3.2-18	Static pressures versus time in the steady driver ejector flow at $X/W = 8.0$ , ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	93
3.3.2-19	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = 8.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	94
3.3.2-20	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = 8.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	95
3.3.2-21	The exit plane static pressure versus time on the primary flow centerline ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) ...	96
3.3.2-22	Exit plane stagnation pressures versus time in the steady driver ejector flow ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	97
3.3.2-23	Exit plane stagnation pressures versus time in the 250 Hz driver ejector flow ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ )	98
3.3.2-24	Static pressures versus time in the steady driver ejector flow at $X/W = 6.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .160$ )	99
3.3.2-25	Static pressures versus time in the 142 Hz driver ejector flow at $X/W = 6.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .160$ )	100
3.3.2-26	Static pressures versus time in the 250 Hz driver ejector flow at $X/W = 6.0$ ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .160$ )	101
3.3.2-27	Static pressures at Station 1 versus time ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .160$ )	102

Figure		Page
3.3.2-28	Static pressures at Station 1 versus time ( $L/W = 13.0$ , $P_{s0}/P_{p0} \approx .070$ ) .....	103
3.3.2-29	Simultaneously recorded values of $P_{p1}$ and $P_{p0}$ versus time at the 142 Hz driver frequency <sup>p1</sup> .....	104
3.3.2-30	Simultaneously recorded values of $P_{p1}$ and $P_{p0}$ versus time at the 250 Hz driver frequency <sup>p1</sup> .....	105
3.3.2-31	$P_{p1}/P_{p0}$ versus time at the 142 Hz driver frequency ....	106
3.3.2-32	$P_{p1}/P_{p0}$ versus time at the 250 Hz driver frequency ....	107
3.3.2-33	Theoretical and experimental values of $P_{s1}/P_{p1}$ versus time .....	108
3.3.2-34	Static pressures versus time at $X/W = 1.333$ with a relatively low back pressure ( $L/W = 13.0$ , $P_{s0}/P_{p0} \approx .070$ )	109
3.3.2-35	$w_s/w_p$ versus $P_{m3}/P_{s0}$ for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .070$ ) .....	110
3.3.2-36	$w_s/w_p$ versus $P_{m3}/P_{s0}$ for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .100$ ) .....	111
3.3.2-37	$w_s/w_p$ versus $P_{m3}/P_{s0}$ for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ , $P_{s0}/P_{p0} \approx .130$ ) .....	112
B.1-1	The single-jet oscillator .....	149
B.1-2	The balance-ended oscillator .....	150
B.1-3	The three-jet interleaved oscillator .....	151
B.1-4	The improved single-jet oscillator configuration .....	152
B.1-5	Single-jet oscillator with centerbody moved away from inlet jet .....	153
B.1-6	Single-jet oscillator with centerbody in position for jet attachment .....	154

Figure		Page
B.1-7	Balance-ended oscillator with flow control vanes in position .....	155
B.1-8	Three-jet interleaved oscillator flow field .....	156
B.1-9	Plexiglass model of the single-jet oscillator .....	157

## 1.0 INTRODUCTION

This investigation of multiple ducted streams with a periodic driver flow was conducted to determine if the periodic driver flow was an effective mechanism to improve the momentum and energy exchange and to enhance mixing between compressible high speed ducted streams. The ducted system investigated was a two-dimensional planar, constant area, air-to-air, supersonic-subsonic ejector. A large scale fluidic oscillator was developed to generate the periodic pulses in the primary driver flow. A theoretical analysis based on the assumptions of a one-dimensional, quasi-steady, inviscid flow was developed and compared with experimental results. An extensive experimental program examining both steady and periodic driver flows in the ejector was carried out.

### 1.1 STATEMENT OF THE PROBLEM

The impetus of this investigation is rooted in fluid-dynamic problems encountered in the development of high energy chemical laser systems. The high Mach number, low pressure streams entering the laser cavity do not readily mix. This results in a short lasing zone and restricted laser power output. The introduction of an unsteady flow into this flow could potentially enhance the mixing between these multiple high speed compressible laser cavity streams by causing large disturbances and vorticity in these flows.

The high temperature, low pressure, corrosive laser cavity flow must be pumped, after exiting the cavity, to the prevailing ambient pressure condition. As discussed later, ejector-diffuser systems are well suited

for this task, despite the fact that the ejector-diffuser is a heavy, bulky, and inefficient addition to the laser system. Walker [1]<sup>†</sup> discusses topics involved in laser-ejector system integration such as packaging multiple ejectors, diffuser requirements, and staging considerations. The opinion was expressed by Walker, et al., that advances in ejector packaging and investigations of the effects of laser system parameters on ejector operation could lead to improved ejector system performances; however, any significant improvement in ejector performance is most likely to be the result of advances in ejector technology.

The overall goals of this research program were to investigate how a periodic driver flow influenced ejector performance parameters and whether a periodic driver flow in an ejector significantly enhanced mixing and momentum exchange between the ducted, high speed, compressible primary and secondary streams.

The investigation had the following specific objectives:

1. To develop an understanding of the mechanisms, processes, and interactions involved in ducted multiple stream flows with a periodic driver;
2. To develop and evaluate a theoretical model for such a system;
3. To determine if a periodic driver flow demonstrates the potential to make ejector systems more compact and/or efficient;

---

<sup>†</sup>Numbers in brackets refer to entries in REFERENCES.

4. To develop a large-scale fluidic oscillator with no moving parts, frequency adjustability, and small losses;
5. To add to the limited technology and data base of such flows.

## 1.2 GENERAL BACKGROUND AND LITERATURE SURVEY

Ejectors are non-mechanical devices used to pump, compress, mix, and convey fluids. Ejector applications include high vacuum systems, ram-jet combustors, thrust augmentation nozzles, nuclear reactor core flow recirculation pumps, and chemical laser pumping systems to name just a few. Ejector system configurations range from one axisymmetric primary driver flow nozzle concentrically directing its flow into a constant area cylindrical mixing tube to a bank of hypermixing nozzles directing skewed driver flows into a variable area rectangular duct [1,2,3].

The basic mechanisms of ejector operation are viscous interaction and mixing between the primary driver and secondary induced flows. Thrust augmentation and the pumping and compression of a secondary flow are the result of the momentum and energy transfer from the primary to secondary flow within the mixing duct of the ejector [4]. During ejector start-up the momentum of the primary driver flow is imparted to the fluid within the mixing duct; this causes a flow towards the open end of the duct. The resulting pressure drop at the inlet end of the mixing duct induces a secondary flow to enter the duct. The primary and secondary flows interact and mix, ideally reaching a fully uniform state at the exit plane of the ejector mixing duct.

A number of analytical methods, differing in levels of sophistication, have been applied successfully to ejector flows. Finite difference techniques were used by Gilbert and Hill [5] to model a two-dimensional planar, variable area, slot nozzle ejector. Hasinger [6] has applied a one-dimensional analysis to a number of ejector mixing modes including constant area, constant pressure, and a defined pressure profile along the mixing duct. Tai [7] has developed a computer code that for given entrance conditions and a wall static pressure distribution determines the ejector wall contour by finite difference techniques. A one-dimensional inviscid analysis was applied by Addy and Mikkelsen [8] to the supersonic-subsonic, constant area ejector. This analysis is based on the method of Fabri and Paulon [9]. The quasi-steady flow ejector analysis developed during this investigation is based on the steady flow ejector analysis of Addy and Mikkelsen. More detailed analyses by Chow and Addy [10,11] and Chow and Yeh [12] of supersonic-subsonic ejector flow use the method of characteristics to determine the initial supersonic primary flowfield and a one-dimensional model of the secondary flow. Viscous effects, variable area inlet sections, and special consideration of low secondary mass flow rates are incorporated into these analyses.

Supersonic-supersonic, constant area ejector-diffuser flow was modeled with a one-dimensional control volume approach by Mikkelsen, Sandberg, and Addy [13]. The one-dimensional theory predicted maximum ejector compression ratios 15 to 20 percent higher than the corresponding experimental values. The supersonic-supersonic, constant area ejector was particularly susceptible to secondary flow separation

which requires a more sophisticated analysis than the one-dimensional theory used.

One-dimensional analyses of ejector flow are limited, in a strict sense, to constant area ducts. Constant pressure and specified pressure distribution mixing modes can be treated by one-dimensional analyses [6,8] but rely on more sophisticated analyses or empiricism to obtain the required wall contour. Viscous interaction between primary and secondary ejector streams can noticeably effect the secondary mass flowrate [10,11,12] under certain flow conditions but one-dimensional analyses do not consider or predict such flow field details. Despite these limitations, theoretical predictions based on the simple one-dimensional approach are generally in good agreement with experimental results.

Extensive bibliographies of ejector literature and papers have been compiled by Addy and Mikkelsen [8,13].

Ejector pumping systems have their advantages and disadvantages when compared to conventional mechanical systems. A detailed comparison of ejector and mechanical pumping systems has been made by Baker and McDermit [14]. The no-moving-parts simplicity and the simple geometry of ejector systems facilitates protective cooling, lining, or coating of wetted ejector surfaces. Ejectors can be fabricated from most materials without difficulty. Thus ejectors often see service where high temperature corrosive fluids are involved, such as in chemical lasers. Ejectors start quickly and respond rapidly to adjust to changing flow conditions. Ejector applications which require large secondary flowrates and high pressure recovery are accomplished by the packaging of ejectors in parallel

and/or series. A diffuser is generally used to further improve the pressure recovery of an ejector system. Such ejector-diffuser systems tend to be heavy and bulky and to require considerable quantities of high pressure primary flow to pump the secondary fluid. Optimum performance of ejector systems is usually limited to a small range of operating conditions and requires total system integration to achieve.

This investigation is based on the premise that a periodic driver flow may enhance the modes of flow interaction beyond those which exist in a steady flow ejector. Turbulent mixing and entrainment, the basic mechanisms involved in steady ejector flows, have been the subject of numerous investigations [15-22]. Experimental evidence indicates that large scale eddies, which evolve from surface waves generated by turbulence induced instabilities at a fluid interface, act as the primary mechanism of entrainment in turbulent shear flows. The rate of entrainment and mixing layer growth depend directly on the intensity of the large scale eddies and indirectly on factors which determine the frequency of eddy generation and the speed of their decay. These large scale structures in the turbulent mixing layers have often been found to be coherent and periodic in nature.

Numerous approaches have been taken to enhance mixing by exciting instabilities in the shear layer of air jets. Crow and Champaign [23] used loudspeakers in a plenum chamber upstream of the exit of a round jet discharging into the atmosphere in an attempt to force latent periodic structures that may exist in the turbulence of the jet mixing layer. Increased entrainment rates and turbulence levels, particularly at the

periphery of the jet, were observed. The virtual origin of the mixing region was shifted approximately two jet diameters upstream with a 2% fluctuation of the exit velocity. Becker and Massoro [24] investigated the instability of an axisymmetric jet with external acoustic stimulation. Pure tones and noise produced both large increases in the mixing layer spread rate and large ring vortices that disintegrated into small scale turbulent eddies. Glass [25] located a reflecting surface near the exit of an overexpanded supersonic jet. Disturbances which were believed to be generated in the shock cells of the supersonic flow, were directed towards the jet exit. Periodic vortex shedding was observed at frequencies as high as 10 kHz. The spread rate and velocity decay of the jet were noticeably increased. McCormack, Cochran, and Crane [26] also obtained increased mixing rates and a shortened potential core by mechanically vibrating a two-dimensional slot nozzle that was discharging air into the atmosphere.

Fully and partially pulsed jets were used in a number of investigations to study the effects unsteady flow had on jet mixing and turbulence. Binder and Favre-Marient [27] used a rotating butterfly valve to pulse an axisymmetric air jet; RMS velocity deviations from the mean of up to 30% were produced at frequencies up to 200 Hz. Centerline velocity decay and spread rates reached their asymptotic values much faster than for the steady jet and the intensity of the turbulence increased more rapidly and remained at higher levels well after pulsations had died away downstream. Bremhorst and Harch [28] fully pulsed an axisymmetric subsonic air jet using mechanically driven rollers that only allowed air flow during approximately 1/3 of each revolution. The entrainment capabilities of the

jet were significantly increased. Olivari [29] examined an axisymmetric jet that was almost fully pulsed. A fluidic back pressure amplifier that used a rotating cam to modulate the control port was used to pulse the flow. Turbulence intensity increased significantly but mixing between the jet and the surrounding fluid was not significantly increased over that of the steady jet. It appears that the Strouhal number,  $St = \omega d/V$ , is a critical parameter in the above studies. Olivari, et al., had  $St$  values of  $8.25 \times 10^{-3}$  and  $22 \times 10^{-3}$  but the other studies, cited above, had  $St$  values from  $69 \times 10^{-3}$  to  $800 \times 10^{-3}$ . In general an increase in the Strouhal number causes an increase in the entrainment of a jet and a more rapid decay of the jet core velocity.

Viets [30] developed an alternative approach to stimulate jet entrainment. A fluidic nozzle was used to induce a jet to oscillate transverse to the flow direction. The jet spread rapidly and takes on a serpentine appearance prior to jet breakup. Platzer, Simmons, and Bremhorst [31] compared the effects on the entrainment of the surrounding fluid of a transverse oscillating jet, fully pulsed jets, and co-axial jets with a partially pulsed core. The fully pulsed jets entrained the most ambient fluid and the partially pulsed and transverse oscillating jet entrained approximately the same amount. All three unsteady jets entrained substantially more flow than a corresponding steady jet.

Ejectors have been the subject of a number of pulsed flow investigations [32-35]. The primary driver flow was fully pulsed by a rotating valve mechanism in each of these studies. "Slugs" of primary flow are discharged into a duct producing compression waves in front of the "slug" and

rarefaction waves behind it. The piston-like wave action of the primary flow "slugs" effectively induced a secondary flow into the duct. The normal mode of energy and momentum exchange in these "wave energy exchangers" is ideally isentropic and more efficient than the irreversible mixing mechanism operating in steady flow ejectors. The secondary-to-primary mass flowrate ratio of the pulsed flow ejector was much larger than the mass flowrate ratio of the corresponding steady flow ejector in certain cases. Since the secondary or induced flow stagnation pressure and the exit plane static pressure were atmospheric, nothing is known of the pressure recovery capabilities or the effects of the back pressure on the performance of this pulsed ejector.

In some cases steady flow ejectors have been found to resonate under certain pressure conditions. Quinn [36] has examined the effects of these screech tones on ejector performance. It appears that resonance may have fixed the frequency of shear layer vortices, thus strengthening them. Increased entrainment and mixing between the secondary and primary flows were observed.

Experimental evidence strongly suggests mixing between multiple ducted streams and ejector performance can be improved by an unsteady periodic driver flow. All but a few of the investigations described above were concerned with a significantly different flow situation than is considered in this investigation; however, turbulent mixing and/or entrainment are essential to each one.

## 2.0 THEORETICAL ANALYSIS OF THE CONSTANT AREA SUPERSONIC-SUBSONIC EJECTOR WITH A PERIODIC DRIVER FLOW

A one-dimensional, quasi-steady analysis was used to model the unsteady ejector flow. A computer code, UCAE, was written to perform this analysis on either experimentally determined input conditions or on a default set of conditions including a periodic sinusoidal driver flow. Figure 2.0-1 indicates the location of the stations and control volume used in the overall analysis. The analysis assumes that uniform supersonic primary and subsonic or sonic secondary streams enter the mixing duct at Station 1, interact and mix, and exit the duct as a uniformly mixed subsonic flow at Station 3. Part of the quasi-steady analysis is based on the method of Fabri and Paulon [9] for the steady flow analysis of an ejector.

### 2.1 EJECTOR FLOW REGIMES

Four ejector flow regimes are considered in this analysis. These flow regimes are characterized by the secondary-to-primary static pressure ratio at Station 1,  $P_{s1}/P_{p1}$ , and whether or not the flow conditions at Station 1 are independent of the back pressure. The "saturated supersonic" regime, SSR, can exist when  $P_{s1}/P_{p1} \geq 1.0$  and  $M_{s1} = 1.0$ . If  $P_{s1}/P_{p1} > 1.0$ , the secondary flow expands against the primary as these streams enter the mixing duct and the minimum secondary flow area is at Station 1. The "supersonic" regime, SR, can exist when  $P_{s1}/P_{p1} < 1.0$  and, as discussed later, when the secondary flow is choked at an aerodynamic throat formed between the primary flow and the duct wall. An "approximate" regime, APPR, is used to model flows which are ideally in the supersonic regime

PREVIOUS PAGE BLANK - NOT FILMED

but due to computational difficulties are most practically modeled by assuming  $P_{s1}/P_{p1} \approx 1.0$ .

The three regimes mentioned above can occur only if the back pressure,  $P_{m3}$ , is sufficiently low. If the back pressure is too high, the secondary flow cannot be choked in the supersonic and saturated supersonic regimes and the  $P_{s1}/P_{p1} \approx 1.0$  condition used in the approximate regime is no longer a good assumption. The "mixed" regime, MR, exists when the back pressure is too high to allow the other regimes to operate. In the mixed regime the subsonic secondary flow conditions at Station 1 are dependent on the back pressure imposed at the exit plane, Station 3. SR, SSR, and APPR flow conditions at Station 1 are always independent of the back pressure.

The flow characteristics which distinguish one flow regime from another are "break-off" conditions. By changing ejector operating conditions, ejector flow can "break-off" from one flow regime to another. For example, SSR flow breaks-off with MR flow at  $M_{s1} = 1.0$  and  $P_{s1}/P_{p1} \geq 1.0$ , the "break-off" conditions. If  $M_{s1}$  is somehow decreased from its "break-off" value of 1.0, the flow breaks-off from SSR to MR flow. The theoretical analysis determines ejector flow parameters at break-off points between the mixed regime and back pressure independent regimes.

For the given input data, the solution procedure used to determine ejector flow conditions at Stations 1 and 3 depends on the basic character of the flow that is possible at Station 1. Each of the four flow regimes considered in this analysis requires a different computational approach. The determination of the flow regimes which can exist within

the ejector is the initial step taken in the analysis. This initial determination requires consideration of the possible secondary-to-primary static pressure ratio at Station 1,  $P_{s1}/P_{p1}$ . The back pressure imposed at the exit plane of the ejector is also used to determine which one of two possible regimes exist, MR or a back pressure independent regime.

If  $P_{s1}/P_{p1} \geq 1.0$ , the regime of operation is either the saturated supersonic or mixed regime. In either case, the secondary flow expands against the primary flow as both streams enter the mixing duct. The minimum secondary flow area is at Station 1 so  $0 \leq M_{s1} \leq 1$ . When the secondary flow is choked,  $M_{s1} = 1$ , the regime is saturated supersonic; otherwise, the mixed regime must exist,  $M_{s1} < 1$ . The mixed regime occurs when the back pressure is too high to allow secondary choking.

Both the supersonic and mixed regimes are possible when  $P_{s1}/P_{p1} < 1.0$ . The primary flow expands against the secondary as each stream enters the duct. It is assumed, after Fabri and Paulon [9], that the primary and secondary streams remain distinct during their initial interactions and that if the back pressure is sufficiently low, the secondary flow is choked at an aerodynamic throat formed between the primary flow and the duct wall. If secondary choking does occur at some location, Station 2, within the duct, see Fig. 2.1-1, the ejector operates in the supersonic regime. An ejector with an unchoked secondary flow is operating in the mixed regime.

SR, SSR, and MR flows do not include all the possible input conditions which require a separate computational solution procedure. The supersonic and saturated supersonic regimes "break-off" into the mixed regime if the secondary flow becomes unchoked, however, the saturated supersonic regime

computationally does not necessarily "break-off" into the supersonic regime at the conditions:  $M_{s1} = 1$  and  $P_{s1}/P_{p1} = 1$ . If a supersonic regime flow is considered, one would expect that as  $P_{s1}/P_{p1}$  is increased the location of the choked secondary flow, Station 2, would approach Station 1 as  $P_{s1}/P_{p1}$  approached a value near 1. Thus,  $M_{s1}$  should approach  $M_{s2}$  or a value of 1. The computational procedure for the supersonic regime solution involves a search algorithm in which  $M_{s1}$  is successively incremented and used as a calculation parameter. Typically for a certain set of input conditions, a value of  $P_{s1}/P_{p1} = 1$  is encountered with  $M_{s1} < 1$ . A supersonic regime solution is no longer obtained and the flow conditions are not at supersonic-saturated supersonic break-off values. The lowest value of  $M_{s1}$  at which this occurs is defined as the critical secondary Mach number,  $M_{crit}$ , and marks the break-off of another computationally distinct regime within the supersonic regime. It has been found that supersonic regime solutions may exist for  $M_{crit} < M_{s1} < 1$ . These solutions all have values of  $P_{s1}/P_{p1}$  very near to 1.0 which is also the break-off condition between the regimes of supersonic and saturated supersonic flow. It appears that solutions in this regime can be well approximated by assuming  $P_{s1}/P_{p1} = 1$ . This "approximate" regime appears to be the result of the sensitivity of the flow at these conditions and the need for greater numerical accuracy. The computational procedure in the supersonic regime involves a search technique and requires iterations to determine a solution by the Fabri criterion at each step of the overall search. It appears that a substantial increase in the overall number of iterations would be required to obtain an accurate SR solution that, at these flow conditions, probably does not significantly differ from the APPR solution.

Theoretically the supersonic, saturated supersonic, and approximate regimes all break-off into the mixed regime flow when the imposed back pressure is greater than the theoretical value at the break-off conditions. However, as previously mentioned, when the back pressure is lower than the break-off value, the flow conditions at Station 1 are unaltered from their break-off values and are independent of the back pressure. Figure 2.1-2 is a sketch to scale of the solution surfaces determined by the analysis for the ejector configuration which was examined experimentally. Break-off values establish the loci of break-off points along which the SR, APPR, and SSR surfaces intersect the MR surface. In the analysis and in Fig. 2.1-2,  $P_{s0}/P_{p0}$  is an input flow condition,  $P_{m3}/P_{s0}$  is the non-dimensional back pressure boundary condition, and  $M_{s1}$  is the dependent variable.

## 2.2 OVERALL CONTROL VOLUME ANALYSIS

The control volume used in the overall analysis is indicated in Fig. 2.0-1. It was assumed that piecewise uniform flows enter the duct at Station 1 and exits subsonically at Station 3 as a uniformly mixed flow. A unique solution is obtained by determining from the input flow conditions which of the flow regimes is possible when the back pressure is sufficiently low. Flow conditions at Station 1 can then be determined. If the back pressure is greater than the break-off value, the mixed regime exists and a unique solution is found by satisfying the back pressure boundary condition. The conservation principles are applied to the overall control volume, Fig. 2.0-1, to determine both the exit plane conditions

at the break-off point and the mixed regime solutions. The overall control volume analysis has a unique solution for the back pressure independent regimes, i.e., the break-off solution. The analysis cannot, for instance, find the exit plane Mach number,  $M_{m3}$ , when the back pressure is less than the break-off value.

The theoretical analysis with an unsteady driver flow was carried-out under the assumption of quasi-steady flow. The periodic input flow conditions were subdivided into time increments and the theoretical analysis was performed during each time increment as if the flow were steady and independent of other time increments. Approximate integral averages of the performance parameters can then be obtained.

The following assumptions are made in the analysis:

1. Quasi-steady flow  $\frac{\partial(\quad)}{\partial t} = 0$  for each time step;
2. Piecewise uniform flow at Station 1;
3. Fully mixed uniform flow at Station 3;
4. Frictional effects within the duct are negligible;
5. No shear or shaft work;
6. Gravitational potential energy changes are negligible;
7. The flow is adiabatic and non-reacting within the duct;
8. Primary and secondary gases are calorically perfect;
9. The primary nozzle base area is negligible; and
10. Flows are brought isentropically from their stagnation states to Station 1.

Continuity may then be expressed as:

$$\oint_{cs} \rho \bar{V} \cdot d\bar{A} = 0 \quad (2.2-1)$$

or

$$\rho_{p1} V_{p1} A_{p1} + \rho_{s1} V_{s1} A_{s1} = \rho_{m3} V_{m3} A_{m3} \quad (2.2-2)$$

If the mass flowrate,  $w = \rho AV$ , is employed, the continuity equation may be written as:

$$w_s + w_p = w_{m3} \quad (2.2-3)$$

or

$$w_{sp} + 1 = w_{m3}/w_p \quad (2.2-4)$$

where  $w_{sp} \equiv w_s/w_p$  is the mass flowrate ratio.

The mass flowrate function is:

$$\frac{w}{PA} \left[ \frac{R}{M_w} \cdot T_0 \right]^{1/2} = M \left[ \gamma \left[ 1 + \left( \frac{\gamma-1}{2} \right) M^2 \right] \right]^{1/2} \equiv f_1(\gamma, M) \quad (2.2-5)$$

Expressing the mass flowrate ratio,  $w_{sp}$ , in terms of the mass flowrate function yields:

$$w_{sp} = \frac{P_{s1}}{P_{p1}} \cdot \frac{A_{s1}}{A_{p1}} \left[ \frac{M_{ws}}{M_{wp}} \cdot \frac{T_{p0}}{T_{s0}} \right]^{1/2} \frac{f_1(\gamma_s, M_{s1})}{f_1(\gamma_p, M_{p1})} \quad (2.2-6)$$

Conservation of momentum in the X or flow direction may be expressed as:

$$\Sigma F_x = \oint_{cs} V_x (\rho \bar{V} \cdot d\bar{A}) \quad (2.2-7)$$

The momentum equation for the overall control volume is:

$$P_{p1} A_{p1} + P_{s1} A_{s1} - P_{m3} A_{m3} = \rho_{m3} A_{m3} V_{m3}^2 - \left( \rho_{p1} A_{p1} V_{p1}^2 + \rho_{s1} A_{s1} V_{s1}^2 \right) \quad (2.2-8)$$

Using the relationship

$$\rho V^2 = P \gamma M^2 \quad (2.2-9)$$

Eq. (2.2-8) can be written as:

$$\frac{P_{s1}}{P_{p1}} \cdot \frac{A_{s1}}{A_{p1}} \left[ 1 + \gamma_s M_{s1}^2 \right] + \left[ 1 + \gamma_p M_{p1}^2 \right] = \frac{P_{m3}}{P_{p1}} \cdot \frac{A_{m3}}{A_{p1}} \left[ 1 + \gamma_m M_{m3}^2 \right] \quad (2.2-10)$$

Substituting Eq. (2.2-6) for  $P_{s1}/P_{p1}$  and expressing  $P_{m3}/P_{p1}$  in terms of the mass flowrate function, Eq. (2.2-5), produces:

$$f_2(\gamma_m, M_{m3}) = \frac{f_2(\gamma_p, M_{p1}) + f_2(\gamma_s, M_{s1}) \left[ \frac{M_{w_p}}{M_{w_s}} \cdot \frac{T_{s0}}{T_{p0}} \right]^{1/2} \cdot w_{sp}}{\left[ \frac{M_{w_p}}{M_{w_m}} \cdot \frac{T_{m0}}{T_{p0}} \right]^{1/2} (1 + w_{sp})} \quad (2.2-11)$$

where the function  $f_2(\gamma, M)$  is defined as:

$$f_2(\gamma, M) \equiv \frac{(1 + \gamma M^2)}{M \left[ \gamma \left( 1 + \frac{\gamma-1}{2} M^2 \right) \right]^{1/2}} \quad (2.2-12)$$

Solving Eq. (2.2-12) for  $M$  produces:

$$M = \left[ \frac{- \left( f_2^2 - 2 \right) \pm \left[ \left( f_2^2 - 2 \right)^2 + 2 \left( \frac{\gamma-1}{\gamma} \right) \left( f_2^2 - \frac{2\gamma}{(\gamma-1)} \right) \right]^{1/2}}{(\gamma-1) \left[ f_2^2 - \frac{2\gamma}{(\gamma-1)} \right]} \right]^{1/2} \quad (2.2-13)$$

Only the subsonic solution of Eq. (2.2-13) is used.

The energy equation can be written in the form:

$$\frac{\partial Q}{\partial t} - \frac{\partial W_{ss}}{\partial t} = \oint_{cs} \left( h + \frac{V^2}{2} + gZ \right) (\rho \bar{V} \cdot d\bar{A}) \quad (2.2-14)$$

Under the foregoing assumptions, the energy equation simplifies to:

$$\oint_{cs} h_0 (\rho \bar{V} \cdot d\bar{A}) = 0 \quad (2.2-15)$$

where  $h_0 \equiv h + V^2/2$ . For adiabatic flow, the overall control volume analysis energy relation is:

$$h_{0s} w_s + h_{0p} w_p = h_{0m3} w_{m3} \quad (2.2-16)$$

Using Eq. (2.2-4) and that  $h_0 = C_p T_0$  produces:

$$\frac{T_{m0}}{T_{p0}} = \frac{1}{(1 + w_{sp})} \frac{(C_p)_p}{(C_p)_m} \left[ 1 + w_{sp} \frac{(C_p)_s}{(C_p)_p} \frac{T_{s0}}{T_{p0}} \right] \quad (2.2-17)$$

Dalton's law of partial pressures is assumed to be applicable to the mixing process within the control volume as a means of determining the mixed flow gas properties at Station 3. Mass flowrate ratios are used to express the mass fractions in the relations for a constant volume mixing process. This is perhaps the most unrealistic part of the quasi-steady approach for non-constant property flows. The properties of the "slugs" of flow currently entering the duct are used to determine the exit plane properties at the same point in time. These conditions at Station 3 are then assumed to be the back pressure conditions affecting the flow at Station 1. If amplitudes and/or phase lags are small this will not result in a significant error. The mixed flow properties expressed in terms of  $w_{sp}$  and the primary and secondary gas properties are:

$$\frac{(C_p)_p}{(C_p)_m} = \frac{1 + w_{sp}}{1 + w_{sp} \frac{(C_p)_s}{(C_p)_p}} \quad (2.2-18)$$

$$\frac{Mw_m}{Mw_p} = \frac{1 + w_{sp}}{1 + w_{sp} \frac{Mw_p}{Mw_s}} \quad (2.2-19)$$

$$\gamma_m = \left[ 1 - \left( \frac{\gamma_p - 1}{\gamma_p} \right) \frac{\left( 1 + w_{sp} \cdot \frac{Mw_p}{Mw_s} \right)}{\left[ 1 + w_{sp} \cdot \frac{\gamma_s}{\gamma_p} \frac{(\gamma_p - 1)}{(\gamma_s - 1)} \frac{Mw_p}{Mw_s} \right]} \right]^{-1} \quad (2.2-20)$$

Using the relationship

$$C_p = \frac{\gamma R}{Mw(\gamma - 1)},$$

the ratio of specific heats can be expressed as

$$\frac{(C_p)_s}{(C_p)_p} = \frac{\gamma_s}{\gamma_p} \cdot \frac{(\gamma_p - 1)}{(\gamma_s - 1)} \frac{Mw_p}{Mw_s}. \quad (2.2-21)$$

Thus the mixed flow gas properties are defined in terms of  $\gamma_s$ ,  $\gamma_p$ ,  $Mw_s$ ,  $Mw_p$ , and  $w_{sp}$ .

The non-dimensional form of the back pressure boundary condition,  $P_{m3}/P_{s0}$  can be found using Eqs. (2.2-4) and (2.2-5). The result is

$$\frac{P_{m3}}{P_{s0}} = \frac{P_{m3}}{P_{p1}} \cdot \frac{P_{p1}}{P_{p0}} \cdot \frac{P_{p0}}{P_{s0}}$$

$$\frac{P_{m3}}{P_{s0}} = \left( \frac{P_{p1}/P_{p0}}{P_{s0}/P_{p0}} \right) \cdot \left[ \frac{T_{m0}/T_{p0}}{Mw_m/Mw_p} \right]^{1/2} \left( \frac{A_{p1}}{A_{m3}} \right) \left( 1 + w_{sp} \right) \frac{f_1(\gamma_p, M_{p1})}{f_1(\gamma_m, M_{m3})} \quad (2.2-22)$$

The preceding relations are used to formulate a solution procedure for the back pressure independent and mixed flow regimes. In this procedure, it is assumed that  $\{\gamma_p, \gamma_s, M_{p1}, P_{m3}/P_{s0}, A_{p1}/A_{m3}, Mw_s/Mw_p, T_{s0}/T_{p0}\}$  are known. In the mixed regime, unknowns include  $\{w_{sp}, P_{s1}/P_{p1}, M_{m3}, M_{s1}, T_{m0}/T_{p0}\}$ . The problem for the back pressure independent regimes has some of these variables specified from the outset.

In the saturated supersonic regime,  $M_{s,1} = 1.0$ ; in the approximate regime,  $P_{s,1}/P_{p1} \approx 1.0$ . The static pressure ratio,  $P_{s,1}/P_{p1}$ , can be determined for a value of  $M_{s,1}$  by the Fabri criterion in the supersonic regime; in this regime,  $M_{s,1}$  is used as a calculation parameter. As presented, the problem is not closed. There are five mixed regime unknowns but only three conservation equations and the back pressure boundary condition are available to determine them. The back pressure independent regimes have four unknowns and three equations. One basic unknown must be specified as a calculation parameter. The secondary-to-primary stagnation pressure ratio has been chosen as the calculation parameter. The pressure ratio,  $P_{s,0}/P_{p,0}$ , is fundamental to both flows and can be experimentally measured versus time without difficulty. Thus  $P_{s,1}/P_{p1}$  can then be determined from the isentropic relation:

$$\frac{P_{s,1}}{P_{p1}} = \frac{\left[ 1 + \left( \frac{\gamma_s - 1}{2} \right) M_{s,1}^2 \right]^{\gamma_s / (1 - \gamma_s)}}{\left[ 1 + \left( \frac{\gamma_p - 1}{2} \right) M_{p1}^2 \right]^{\gamma_p / (1 - \gamma_p)}} \cdot \left( \frac{P_{s,0}}{P_{p,0}} \right) \quad (2.2-23)$$

for a given  $M_{s,1}$ ; the problem is closed.

### 2.3 SUPERSONIC REGIME ANALYSIS

A control volume analysis, see Fig. 2.1-1, which is based on the method of Fabri and Paulon [9] has been used to determine supersonic regime secondary flow conditions at Station 1. Due to the interaction between the primary and secondary streams within the duct, the assumption is made that the secondary flow chokes within the duct at Station 2 and that the secondary and primary flows separately co-exist to fill the duct.

The pressure ratio,  $P_{s1}/P_{p1}$  is found for an assumed value of  $M_{s1}$  by applying the conservation of mass and momentum between Stations 1 and 2.  $M_{s1}$  is determined by iteration by a search routine until the value of  $P_{s1}/P_{p1}$  obtained from the Fabri criterion agrees with the value resulting from input conditions:  $M_{p1}$ ,  $P_{s0}/P_{p0}$ , and the assumed  $M_{s1}$ .

The following assumptions have been made:

1. The primary and secondary streams remain distinct and uniform between Stations 1 and 2;
2. The mean pressures of the primary and secondary flow may differ at any cross section;
3.  $P_{s1}/P_{p1} < 1.0$ ;
4.  $M_{s2} = 1.0$ ;
5. The flow is isentropic;
6. The body forces are negligible;
7. The wall friction can be neglected;
8. No shear or shaft work;
9. The primary nozzle base area is negligible; and
10. The flows are brought isentropically from their stagnation states to Station 1.

The area ratio,  $A_{s1}/A_{s2}$ , can be expressed with the area ratio function,  $A/A^*$ ,

$$A/A^*(\gamma, M) = \frac{1}{M} \left[ \frac{2}{(\gamma+1)} \cdot \left[ 1 + \frac{(\gamma-1)}{2} M^2 \right] \right]^{\gamma+1/2(\gamma-1)} \equiv f_3(\gamma, M) \quad (2.3-1)$$

as

$$A_{s1}/A_{s2} = A/A^*(\gamma_s, M_{s1})$$

since  $M_{s2} = 1$ . The flow area available to the primary at Station 2 and the determination of  $M_{p2}$  follow directly from the conservation of mass; the relationship is

$$A/A^*(\gamma_p, M_{p2}) = A/A^*(\gamma_p, M_{p1}) \cdot \frac{A_{p2}}{A_{p1}}$$

or

$$f_3(\gamma_p, M_{p2}) = f_3(\gamma_p, M_{p1}) \left[ \frac{1 - \frac{(1 - A_{p1}/A_{m3})}{A_{s1}/A_{s2}}}{A_{p1}/A_{m3}} \right] \quad (2.3-2)$$

$M_{p2}$ , found numerically, must be greater than  $M_{p1}$ .

Conservation of momentum between Stations 1 and 2 produces:

$$\begin{aligned} P_{s1} A_{s1} (1 + \gamma_s M_{s1}^2) + P_{p1} A_{p1} (1 + \gamma_p M_{p1}^2) &= P_{s2} A_{s2} (1 + \gamma_s) \\ &+ P_{p2} A_{p2} (1 + \gamma_p M_{p2}^2) \end{aligned} \quad (2.3-3)$$

Dividing by  $P_{p1} A_{p1}$  and rearranging for computational simplicity, the expression for  $P_{s1}/P_{p1}$  is:

$$\frac{P_{s1}}{P_{p1}} = \frac{\left( \frac{P_{p2}/P_{p0}}{P_{p1}/P_{p0}} \right) \cdot \left( \frac{A_{p2}/A_p^*}{A_{p1}/A_p^*} \right) \cdot (1 + \gamma_p M_{p2}^2) - (1 + \gamma_p M_{p1}^2)}{\left[ \frac{1 - A_{p1}/A_{m3}}{A_{p1}/A_{m3}} \right] \left[ (1 + \gamma_s M_{s1}^2) - \left( \frac{P_{s2}/P_{s0}}{P_{s1}/P_{s0}} \right) \cdot \left( \frac{1 + \gamma_s}{A_{s1}/A_s^*} \right) \right]} \quad (2.3-4)$$

With the input values of  $\{\gamma_s, \gamma_p, M_{p1}, A_{p1}/A_{m3}\}$  and an assumed trial value of  $M_{s1}$ , Eq. (2.3-4) can be solved after determining  $M_{p2}$  from Eq. (2.3-2) and the isentropic relations. The supersonic regime solution for flow conditions at Station 1 has been completed when a value of  $M_{s1}$  is found that results in convergence of the values of  $P_{s1}/P_{p1}$  determined from Eqs. (2.2-23) and (2.3-4).

## 2.4 COMPUTATIONAL PROCEDURE

The steps in the computational procedure are:

1. To determine which back pressure independent regime can exist, if the back pressure is sufficiently low, at the assumed value of the calculation parameter,  $P_{s0}/P_{p0}$ ;
2. To use the appropriate Station 1 conditions and the overall control volume analysis to determine the resulting exit plane break-off conditions; and
3. To perform an iteration for a mixed regime solution if the back pressure condition imposed at the exit plane is greater than the break-off value determined in item 2 above.

The first step taken to determine which back pressure independent flow regime can exist is to determine the flow conditions at which the supersonic and approximate flow regimes break-off from one another.  $M_{crit}$ , the break-off value between these regimes of the secondary flow Mach number at Station 1, is found by carrying out the supersonic regime analysis in Section 2.3 with assumed values of  $M_{s1}$ . The minimum value of  $M_{s1}$  which produces  $P_{s1}/P_{p1} = 1.0$  from Eq. (2.3-4) is the critical Mach number,  $M_{crit}$ . The search for  $M_{crit}$  is not difficult because  $P_{s1}/P_{p1}$  increases monotonically with  $M_{s1}$  in the supersonic regime. The corresponding break-off value of  $P_{s0}/P_{p0}$  is found using the relation

$$\left( \frac{P_{s0}}{P_{p0}} \right)_{crit} = \frac{P_{p1}/P_{p0}}{P_{s1}/P_{s0}} \cdot \frac{P_{s1}}{P_{p1}} \quad (2.4-1)$$

where the isentropic relations and  $P_{s1}/P_{p1} = 1.0$  are used.

The possibility of a SSR flow can be determined by assuming  $M_{s1} = 1.0$  and solving for the resulting value of  $P_{s1}/P_{p1}$ . The relation is

$$\frac{P_{s1}}{P_{p1}} = \frac{\left(\frac{P_{s1}}{P_{s0}}\right) \left(\frac{P_{s0}}{P_{p0}}\right)}{\left(\frac{P_{p1}}{P_{p0}}\right)} \quad (2.4-2)$$

If  $P_{s1}/P_{p1} \geq 1.0$ , either the saturated supersonic or mixed flow regime must exist. When  $P_{s1}/P_{p1} < 1.0$  and  $P_{s0}/P_{p0} > \left(P_{s0}/P_{p0}\right)_{crit}$ , the flow regime must be either approximate or mixed. Either the supersonic or the mixed regime exist for values of  $P_{s0}/P_{p0}$  lower than  $\left(P_{s0}/P_{p0}\right)_{crit}$ . Thus, as previously discussed, back pressure independent flow conditions at Station 1 are determined.

The overall control volume analysis is then used to determine the flow conditions at Station 3. This is accomplished by solving in order Eqs. (2.2-23), (2.2-6), (2.2-20), (2.2-21), (2.2-18), (2.2-19), and (2.2-17) for  $P_{s1}/P_{p1}$ ,  $w_{sp}$  and mixed flow gas properties.  $P_{s1}/P_{p1} \approx 1.0$  is assumed for APPR flow so Eq. (2.2-23) is used to determine  $M_{s1}$ .  $M_{m3}$  is found by solving Eqs. (2.2-11) and (2.2-13). Only the subsonic solution of Eq. (2.2-13) is considered. The break-off back pressure ratio,  $P_{m3}/P_{s0}$ , is determined by using Eq. (2.2-22). If the imposed back pressure ratio is greater than this break-off value, the mixed regime exists. In the mixed regime, an iterative procedure is necessary to find the value of  $M_{s1}$  which causes  $P_{m3}/P_{s0}$  to converge to the given value. Each iteration for a MR solution must start with Eq. (2.2-23) and then proceed with the overall control volume analysis as discussed above.

A computer code, UCAE, was written to perform this analysis. Section 6.0, the APPENDIX, contains UCAE and a sample input and output.

## 2.5 PARAMETRIC STUDY

A parametric study of theoretical ejector results was made with UCAE for a wide range of  $P_{s0}/P_{p0}$  values. The input conditions used for this parametric study correspond to the experimental setup. Values of  $w_{sp}$ ,  $P_{s1}/P_{p1}$ ,  $M_{s1}$ , and  $P_{m3}/P_{s0}$  at the break-off conditions of the back pressure independent regimes with the mixed regime are plotted versus  $P_{s0}/P_{p0}$  in Figs. 2.5-1, 2.5-2, 2.5-3, and 2.5-4. The lowest value of  $P_{s0}/P_{p0}$  plotted in these figures corresponds to  $M_{s1} = .001$ , the minimum value considered by UCAE.

The mass flowrate ratio, Fig. 2.5-1, is a smooth monotonic function of  $P_{s0}/P_{p0}$ , increasing with  $P_{s0}/P_{p0}$  in all three back pressure independent flow regimes. The slight change in slope between the SR and SSR segments of the curve occurs gradually over the APPR segment of the curve.

The static pressure ratio,  $P_{s1}/P_{p1}$ , is a linear function of  $P_{s0}/P_{p0}$  for SSR flow but is nonlinear for SR flow, see Fig. 2.5-2. Discontinuities exist in the  $P_{s1}/P_{p1}$  solution at the SR-APPR break-off and the APPR-SSR break-off. The SR-APPR discontinuity is due to the  $P_{s1}/P_{p1} = 1.0$  approximation for APPR flow and insufficient numerical accuracy, as previously discussed. The APPR-SSR discontinuity is due to the constant secondary choked flow area in SSR flow which imposes an additional constraint on the nature of the solution. This is more apparent in the plot of  $M_{s1}$  versus  $P_{s0}/P_{p0}$ , Fig. 2.5-3.

Figures 2.5-4 and 2.5-1 shows the relationship existing between ejector pressure recovery and mass flowrate performance. Large mass flowrates are obtained in the saturated supersonic regime at the sacrifice of

the pressure recovery. The converse is true for supersonic regime flows at lower values of  $P_{s0}/P_{p0}$ .

Figures 2.5-3 and 2.5-4 are the normal projections of the loci of break-off points between the mixed and back pressure independent flow regimes, as shown in Fig. 2.1-2, onto the  $(P_{s0}/P_{p0}, M_{s1})$  and  $(P_{s0}/P_{p0}, P_{m3}/P_{s0})$  planes, respectively.

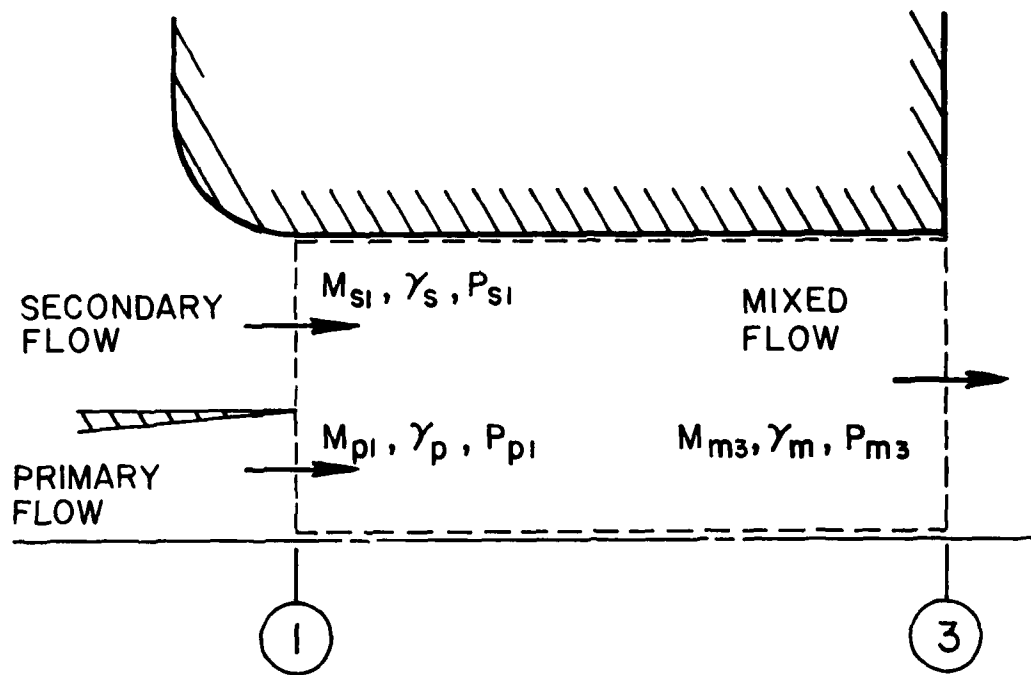


Figure 2.0-1 Control volume used in the overall analysis

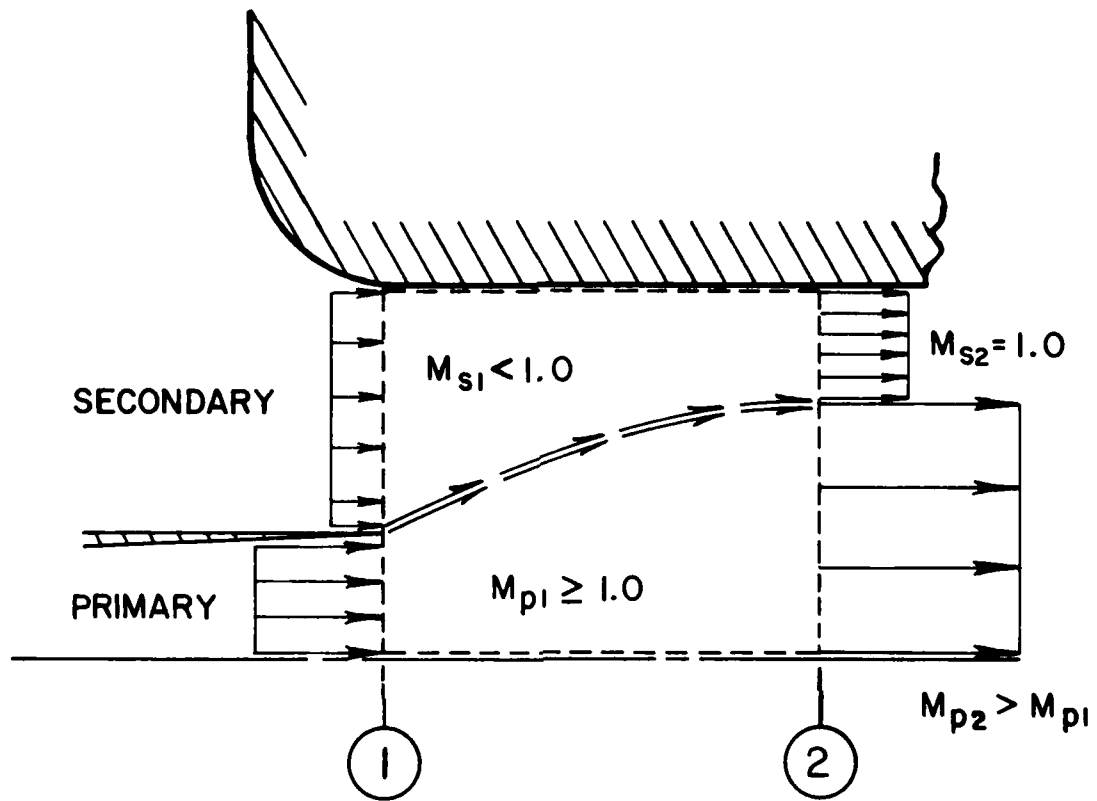


Figure 2.1-1 Control volume used in the supersonic regime analysis

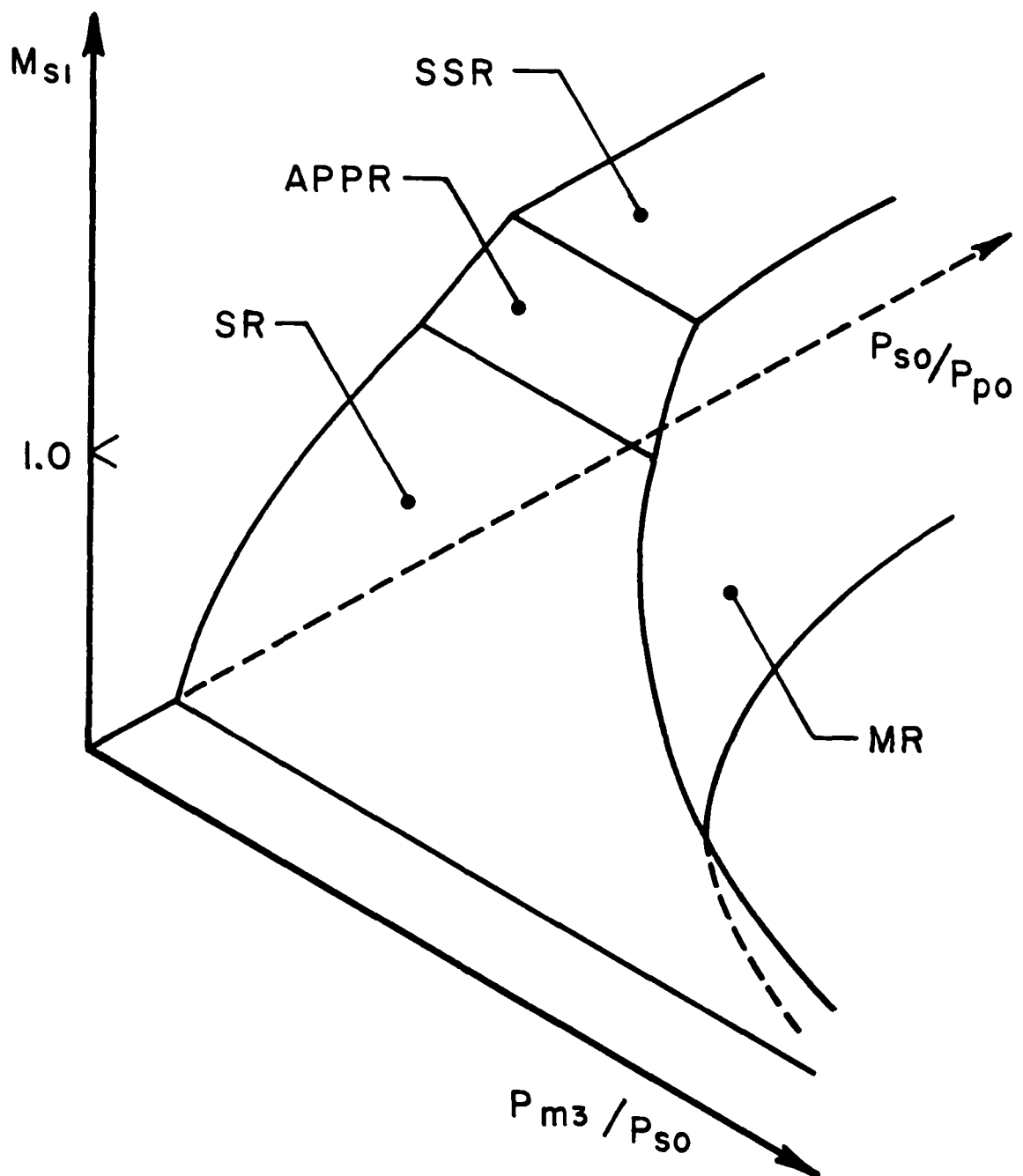


Figure 2.1-2 The one-dimensional inviscid analysis solution surfaces

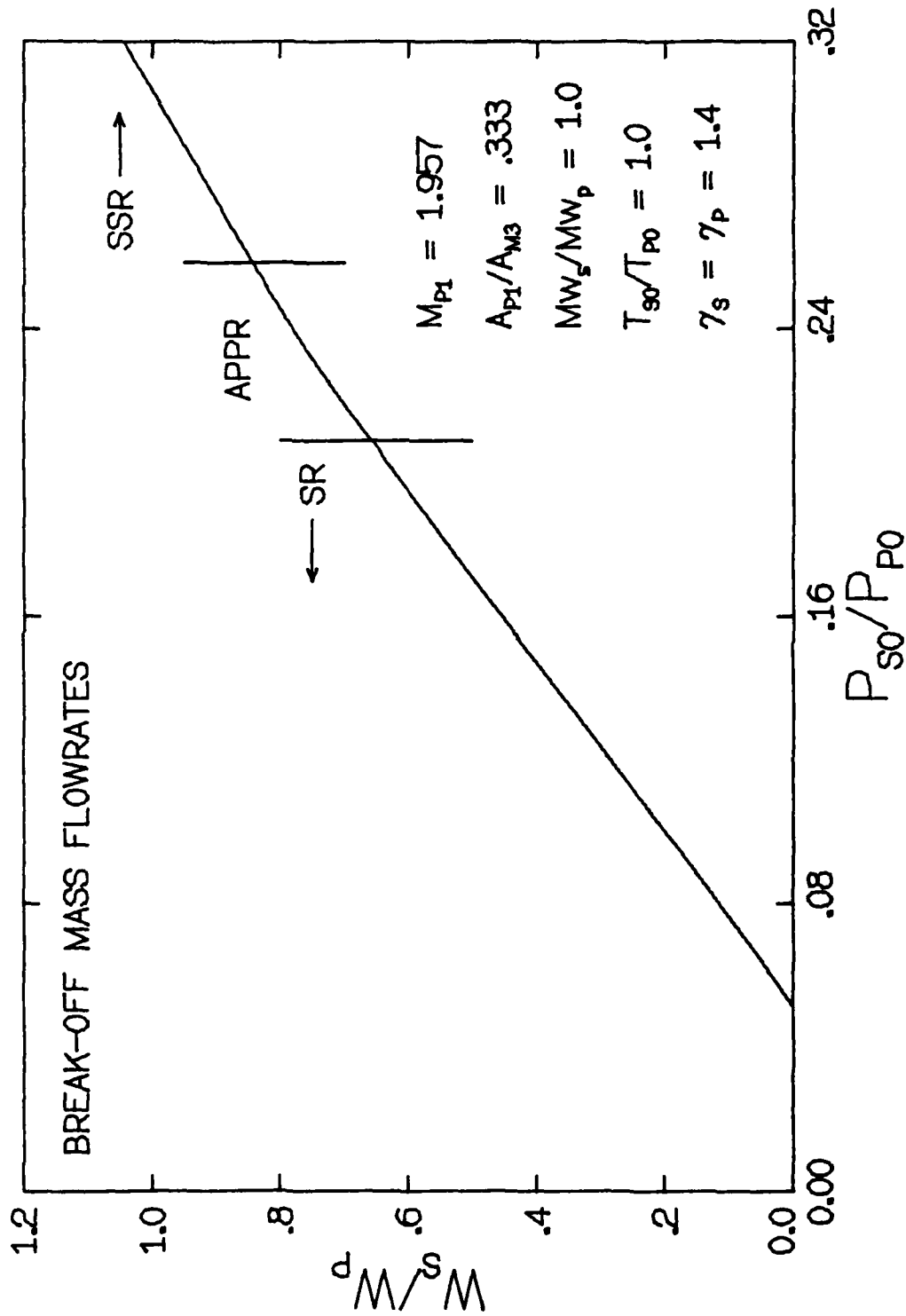


Figure 2.5-1 Theoretical mass flowrate characteristics of the back pressure independent flow regimes versus  $P_{s0}/P_{p0}$ .

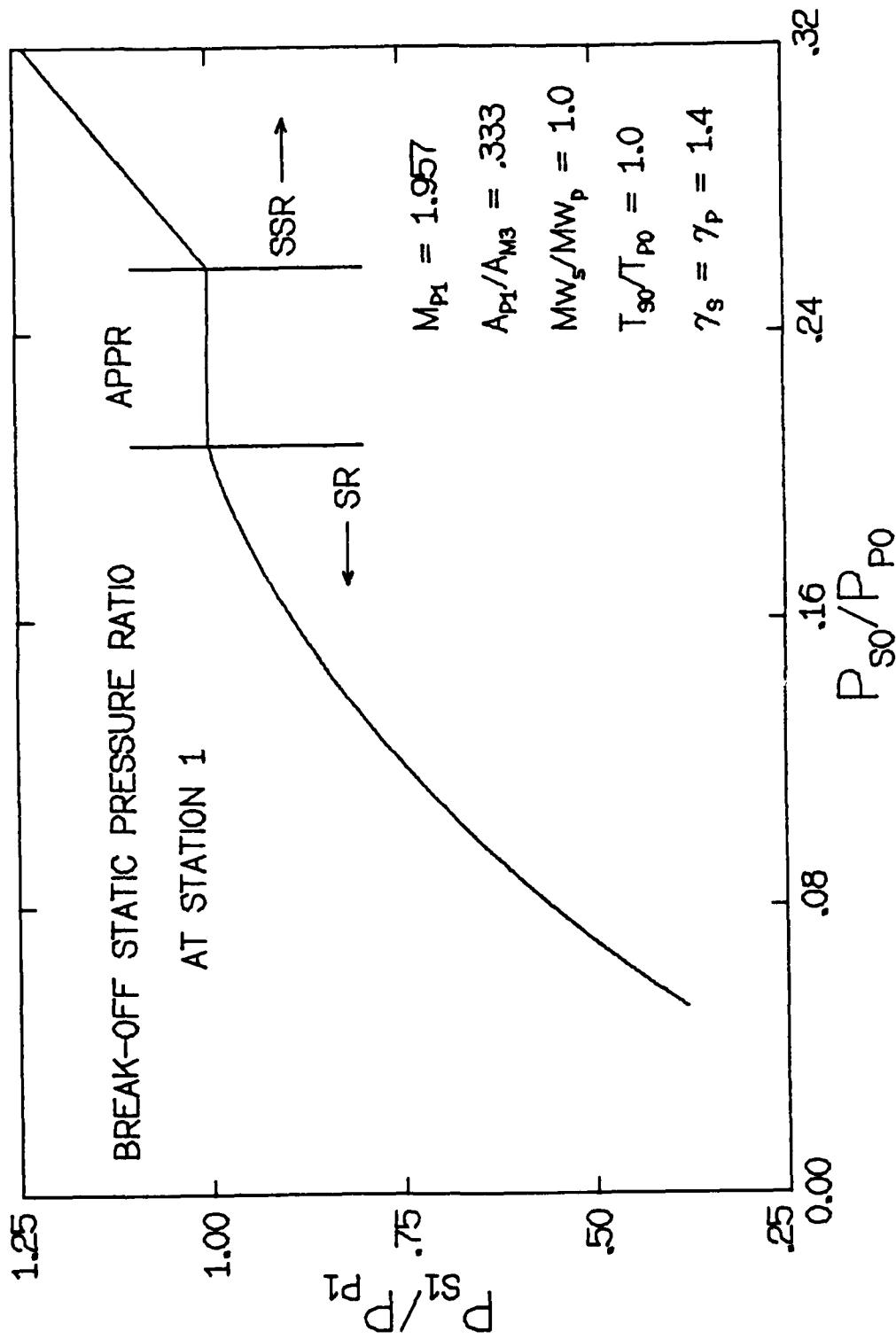


Figure 2.5-2 Theoretical characteristics of  $P_{s1}/P_{p1}$  for the back pressure independent flow regimes versus  $P_{s0}/P_{p0}$

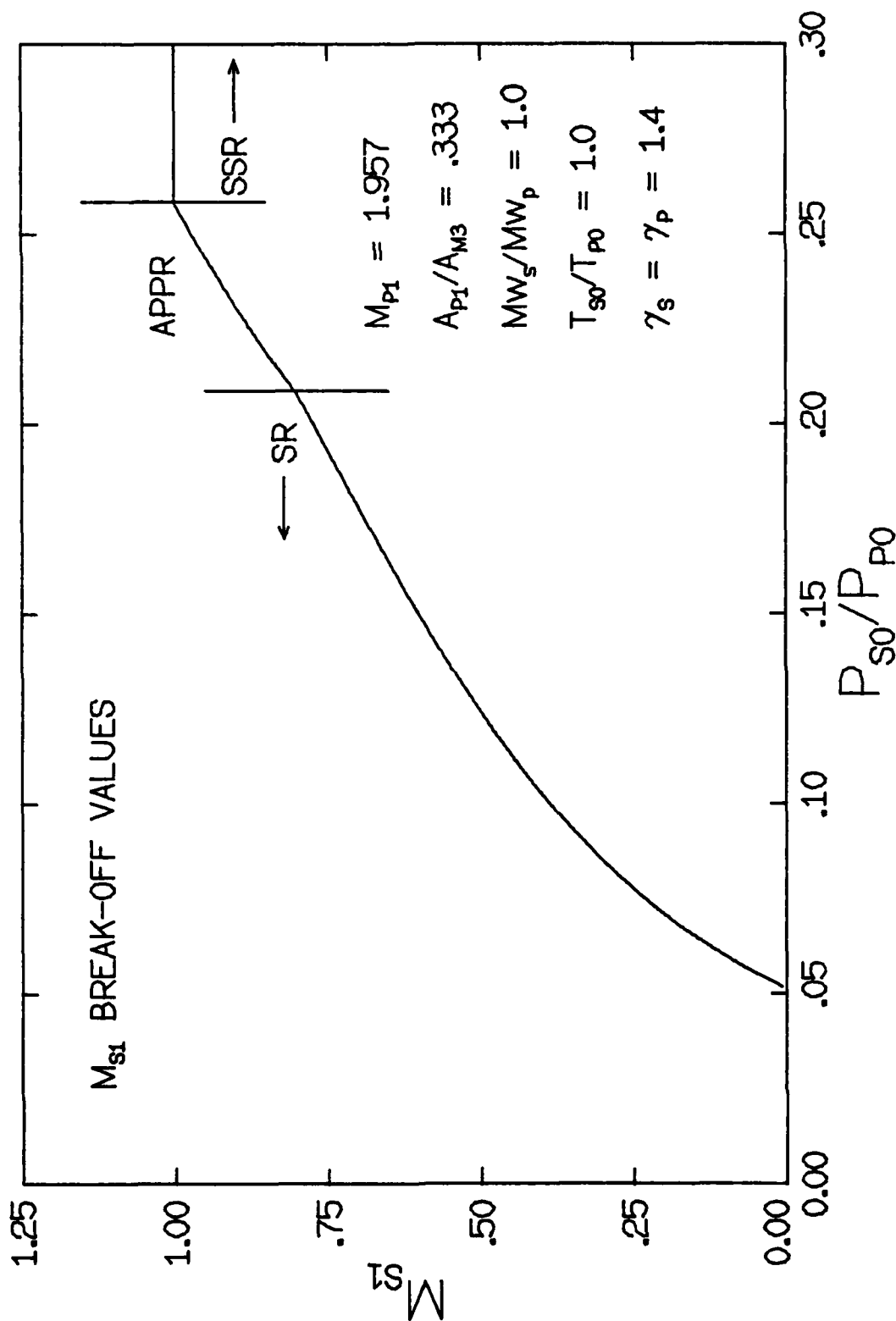


Figure 2.5-3 Theoretical values of  $M_{s1}$  for the back pressure independent flow regimes versus  $P_{s0}/P_{p0}$

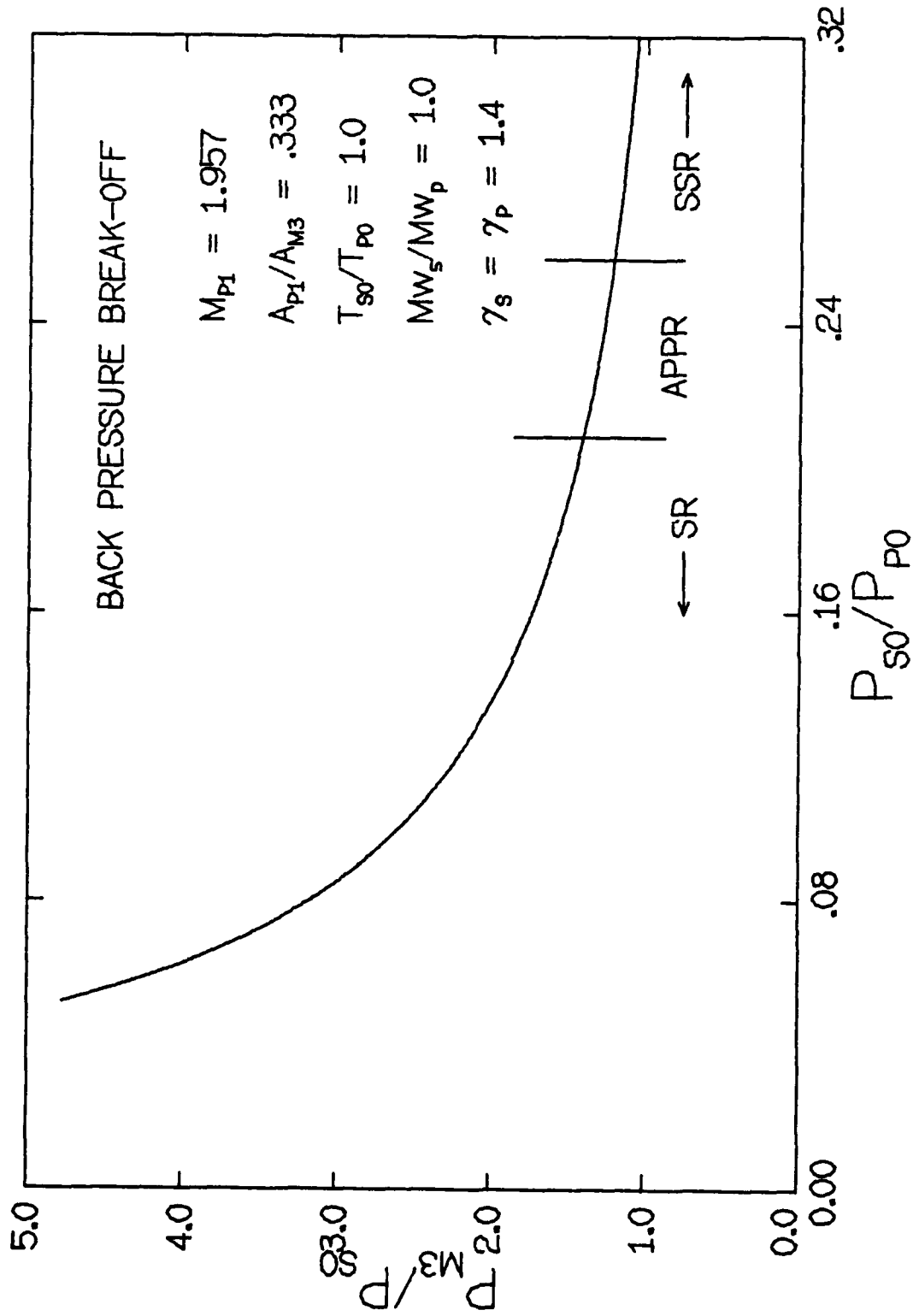


Figure 2.5-4 Theoretical values of  $P_{M3}/P_{S0}$  at which SR, APPR, AND SSR flows break-off to MR flow versus  $P_{S0}/P_{P0}$

### 3.0 THE EXPERIMENTAL PROGRAM

A series of small-scale cold air flow experiments were conducted at the University of Illinois Mechanical Engineering Laboratory to determine what effects a continuous periodic driver flow had on the performance and flow characteristics of a two-dimensional, planar supersonic-subsonic ejector. A wide range of operating conditions were examined with both steady and unsteady primary driver flows.

#### 3.1 EXPERIMENTAL APPARATUS

Filtered and dried compressed air at a maximum pressure level of 850 kPa was supplied from a compressor connected to a 100 m<sup>3</sup> storage tank farm. Steady-state operation was possible for experiments requiring mass flowrates of approximately 1 kg/s or less of compressed air. This air supply system was the source of primary flow in all ejector experiments.

The continuous flow test facility, which was used to run these experiments, consists of two test stands and a central control panel. Each test stand has a two and a three inch compressed air supply line. The stagnation pressure in either line can be adjusted independently at the control panel by air operated control valves. Two sets of U-tube manometers on the control panel are used to measure pressure differences across VDI standard nozzles to determine mass flowrates. Control panel switching allows the selection of U-tube manometers with fluid specific gravities of 1.0, 2.95, or 13.7. A Wallace and Tiernan Series 1500 0-150 psia pressure gage with a .0667% full scale accuracy was used to

measure pressures at various line and test locations and to calibrate some pressure transducers. A Wallace and Tiernan precision manometer and a control panel regulated vacuum source were also used for pressure transducer calibration. Each test stand has 20 pressure taps connected to a 40 tube mercury manometer board. The manometer board was used to measure the secondary stagnation pressure and to obtain a quick visualization of the approximate static pressure distribution within the ejector mixing duct.

The ejector primary flow was taken from a 2-inch supply line on one of the test stands. A VDI standard nozzle, located upstream of the test stand, was used to measure primary mass flowrates. The supply line was reduced to  $1\frac{1}{4}$  inch pipe at the test stand source. A hose fitting was machined from a standard  $1\frac{1}{4}$  inch pipe nipple so that nylon reinforced flexible tubing could be used to connect the primary flow directly to the ejector inlet for steady experiments or to the inlet of a large-scale fluidic oscillator for the unsteady driver flow experiments. Figure 3.1-1 is a schematic of the experimental apparatus which details primary and secondary flow lines.

The secondary flow was induced through a smooth elliptical inlet nozzle from the atmosphere. A VDI standard nozzle block, located in the middle of a 2.13 m length of seamless 2-inch tubing, was used to determine the secondary mass flowrate. The flow was throttled with a gate valve to the desired stagnation pressure after it had passed through the VDI nozzle and a  $.35 \text{ m}^3$  holding tank. A four port manifold was used to distribute the flow to the secondary inlets on the ejector unit. The

threaded holes seen in Figs. 3.1-2 and 3.1-3 are the secondary flow inlet ports.

The holding tank, mentioned above, was used to avoid mass flowrate measurement errors typically encountered when a metering orifice or nozzle is used in the measurement of an unsteady flow. The deviation due to unsteady or pulsatile flow of the metering device discharge coefficient from steady flow values is not well understood. Investigations [37,38] have shown that frequency, amplitude, wave form, and the pressure difference across a flow metering device all have to some degree an effect on the discharge coefficient in a periodic flow. A decoupling of the dynamic pressure difference across the metering device with the velocity through it as well as vortex shedding phenomena due to the unsteady flow are suspected of erroneously altering mass flowrate measurements. Pressure drops across a metering nozzle or orifice in a periodic flow are not representatively measured by U-tube manometers.

For experiments conducted with pulsating flow, the holding tank adds sufficient capacitance to the secondary flow system so that pulsations are damped in the flow to a negligible level at the VDI standard nozzle. The holding tank that was used has more than adequate volume to damp the flow according to the Hodgson number criterion discussed by Ower and Pankhurst [39].

Pulsation of the primary flow was achieved with a large-scale fluidic oscillator. No moving parts, simplicity, small losses, and frequency and amplitude variability were reasons for using a fluidic device to produce the pulsations in the driver flow. An initial effort during this program

involved the selection and development of a fluidic oscillator configuration to produce the pulsating primary ejector flow. Scale models of promising fluidic oscillator geometries were fabricated from styrofoam for performance testing using the hydraulic analogy. The hydraulic analogy is a convenient way to study and visualize unsteady compressible flow; thus it provided a qualitative means to understand the factors influencing the oscillator performance [40]. The particular oscillator configuration used in the air flow experiments was chosen because of its capability to self excite, its pressure level insensitivity, frequency stability, its large amplitude pulses, and the ease with which its operating frequency can be varied. Essentially the same oscillator configuration was used by Halbach, Otsap, and Thomas in a fluidic temperature sensor [41].

This oscillator consists of a fluid jet which impinges on a knife-edge, a feedback loop, and a resonance chamber; the body of the oscillator is shown in Fig. 3.1-4. A jet impinging on a knife-edge is in a bi-stable condition; the jet tends to flip to one side of the knife-edge or the other. This flipping action results in a pressure pulse moving through the portion of the oscillator fed by the jet. Pulses are either reflected back to the jet at the end of the resonance chamber or looped back to the jet through the feedback loop; in either case, the interaction with the jet causes the jet to flip to the other side of the knife-edge. The resonance chamber has an opening at the reflecting end, as shown in Fig. 3.1-5, through which the periodic primary driver flow enters the ejector. Flexible tubing made up a part of the resonance chamber between the ejector inlet and the oscillator body. Similarly, the feedback loop was completed

outside of the body of the oscillator with flexible tubing and a machined  $180^\circ$  turn. Oscillator frequencies were adjusted by changing the lengths of the resonance chamber and the feedback loop tubing. Stagnation pressure probes were located in the hose fitting connecting the source flow to the oscillator inlet and in the hose fitting at the reflecting end of the resonance chamber. The latter stagnation pressure probe was located immediately upstream of the ejector primary flow inlet.

The oscillator knife-edge can be moved along its centerline, see Fig. 3.1-4, so that the distance between the oscillator inlet and the knife-edge can be varied. However, the oscillator knife-edge was always positioned for the maximum oscillator inlet to knife-edge distance allowed by the geometry of the oscillator body. Hydraulic analogy findings indicated that this position, for the given fixed oscillator inlet and exit flow areas, would probably produce the largest amplitude pulses [42]. This knife-edge position avoided possible vibration problems which an extended knife-edge could have created. However, this oscillator configuration was limited to only one pulse amplitude for a given operating frequency and oscillator inlet stagnation pressure.

A planar two-dimensional, constant area, supersonic-subsonic ejector was built for this investigation. The primary flow enters the ejector mixing duct through a continuous slope converging-diverging nozzle designed for a uniform Mach 2 exit plane flow by the method of characteristics with a boundary layer displacement thickness correction. From a stagnation pressure traverse across the exit plane of this nozzle, a reasonably uniform flow was found with Mach numbers in the range:  $1.98 \leq M \leq 2.01$ . This

was a pleasant surprise because the nozzles were cut rather thin near the exit plane to minimize the base area between primary and secondary flows; see Figs. 3.1-3 and 3.1-6. The machining process left the nozzle blocks slightly warped and it was necessary to straighten them. To correct sealing problems, multiple assembly-disassembly operations were initially required. Based on static pressure measurements taken after the final assembly of the ejector, the centerline exit plane Mach number was found to be approximately  $M_{p1} \approx 1.96$ .

The ejector unit itself consists of two types of assemblies. A base assembly in which secondary and primary flows are brought to their confluence point, Fig. 3.1-6, and three aluminum mixing duct assemblies, Fig. 3.1-7. The base assembly was made primarily from stainless steel to improve its dimensional stability, to increase its mass, and to reduce vibration. The supersonic primary flow enters at the center of the mixing duct inlet interleaved between two subsonic secondary streams. The nominal width,  $W$ , of the constant area rectangular mixing duct; i.e., the distance across both secondary and the primary streams, is 33.07 mm. The distance from the primary flow centerline to a secondary flow wall, half of the width, is 16.54 mm and is indicated in Fig. 3.1-6. The height of the mixing duct, the dimension normal to the page in Fig. 3.1-6, is 15.24 mm. The primary to mixing duct flow area ratio is  $1/3$ . Static pressure taps are located along the centerline of each of the four mixing duct walls. The first four pressure tap locations are at intervals of  $X/W = 1/3$  the duct width,  $W = 33.07$  mm. The remainder of the taps are at one duct width intervals in the  $X$  or flow direction starting at  $X/W = 2.0$ .

The base assembly pressure taps and the secondary stagnation pressure probes can be seen in Figs. 3.1-6 and 3.1-3. Static pressure taps are located in the center of the primary and secondary flow inlets at Station 1 and on the primary flow centerline of each mixing duct assembly very near the exit plane. The three mixing duct assemblies produce total duct length-to-width ratios of 5, 9, and 13, when mounted on the base assembly. The  $L/W = 5$  combination was found to be too short to be of practical interest. The shortest duct assembly was modified so that it could be attached to the longest mixing duct. Thus, a mixing duct of  $L/W = 16.374$  could be investigated.

A back pressure valve and muffler were connected to the exit plane of the ejector. The back pressure valve was always kept open and was not used to adjust the exit plane pressure. The valve was mounted on a sealing plate, thus providing a chamber into which the ejector flow discharged. The muffler attached directly to the back pressure valve. A stagnation pressure probe was mounted on the sealing plate and was used to measure the stagnation pressure at the center of the exit plane and at a point  $3/8$  of the duct width off of center.

Figures 3.1-8 and 3.1-9 are two views of the assembled flow system. The oscillator is located on the right in both figures; the resonance and feedback tubes were set-up for a 142 Hz operating frequency. The back pressure valve and muffler are located on the left. The holding tank is behind the oscillator.

An electronic data acquisition system capable of recording four channels simultaneously was used to collect the data for all unsteady

experiments. Pressures were measured with CEC type 4-312 strain gage pressure transducers. These transducers were mounted in case assemblies or line adapters. Scanivalve "zero" volume line adapters were used; these line adapters were designed for use with CEC type 4-312 transducers and are designed to minimize the volume around the transducer diaphragm within the adapter. Figure 3.1-10 is a cross-sectional view of the Scanivalve "zero" volume line adapter with a transducer in place. Each transducer had a cap custom fitted to its diaphragm in accordance with Scanivalve specifications. Pressure waveform distortion due to adapter and pressure line capacitance was minimized by using the Scanivalve adapters and by keeping the connecting pressure lines as short as possible. A 20 mm long piece of #16 gage flexible tubing was used to connect these transducer line adapters to the pressure taps on the ejector unit. All distances between ejector pressure taps and transducer diaphragms were less than 75 mm. CEC type 1-183 signal conditioners were used to excite, balance, and calibrate the transducers as well as to provide an amplified output. Figure 3.1-11 is a schematic of the instrumentation system used.

The signal conditioner output was recorded with a Biomation 1015 waveform recorder. This unit is capable of recording four channels simultaneously at sampling rates as high as 100 kHz. Both analog and digital output were available from the Biomation, thus allowing the examination of data on an oscilloscope before initiating the recording of the digital output on tape. The digital output from the Biomation was recorded with a Memodyne model 2146 digital cassette recorder. A Datos 305 data interface was used to present the Biomation digital output in an

acceptable form with formatting to the Memodyne recorder. A Data Works Model 1700 was used to do this for some of the initial experiments.

A Texas Instruments Silent 700 ASR terminal was used to transmit the recorded data to a CDC CYBER 175 computer.

### 3.2 EXPERIMENTAL PROCEDURE

Cold flow air experiments were conducted to study and compare steady and unsteady ejector performance characteristics. All experiments were conducted at stagnation pressure ratios,  $P_{s0}/P_{p0}$ , that would produce supersonic regime flow at sufficiently low values of  $P_{m3}/P_{s0}$ . As can be seen in Figs. 2.1-2 and 2.5-4, the maximum pressure recovery in the back pressure independent flow regimes, which occurs at the break-off point with MR flow, is noticeably less for SSR and APPR flows than SR flow. Since this investigation is concerned with high pressure recovery applications of ejector systems, the objectives of this investigation can most efficiently be met by investigating only the SR flow range of values of  $P_{s0}/P_{p0}$ . Also, a pressurized secondary system would have been required to investigate SSR and APPR flows. It can also be seen in Fig. 2.1-2 that higher  $P_{m3}/P_{s0}$ , according to the theoretical analysis, are obtained in MR flow than SR flow. Thus MR flow, near break-off with SR flow, was investigated to obtain a more complete understanding of ejector performance near break-off.

The effects of a pulsing driver flow, its frequency, the back pressure, and the mixing duct length on ejector performance and the behavior of the flow within the mixing duct were investigated for evidence of

significant variations in mixing and pressure recovery processes as well as ejector entrainment characteristics. Ejector flow data were also taken to determine how well the analysis predicts flow conditions at Station 1 for both steady and periodic primary flow.

### 3.2.1 Steady Flow Experimental Procedure

An extensive set of steady flow experiments was conducted in order to gain a detailed knowledge of the ejector operating characteristics and to form a basis with which an unsteady driver flow could be judged.

Preliminary experiments were conducted to determine at what values of  $P_{r3}/P_{s0}$  SR flow began to break-off to MR flow and how  $w_s/w_p$  decreased as  $P_{m3}/P_{s0}$  was increased beyond the break-off value. These experiments were accomplished by adjusting the stagnation pressures to different levels so that their ratio,  $P_{s0}/P_{p0}$ , remained constant while the back pressure condition,  $P_{m3}/P_{s0}$ , varied. During these experiments  $P_{m3}$  remained approximately constant. The mass flowrate ratio proved to be quite sensitive to the back pressure; it decreased as  $P_{r3}/P_{s0}$  increased once the ejector flow had passed break-off conditions and was in the mixed regime. It was learned that the mixing duct static pressure profile could be used as a reliable indicator of whether or not break-off of SR to MR flow had occurred and to what extent. This was helpful in conducting the experiments since the flow began to break-off at lower values of  $P_{m3}/P_{s0}$  and more gradually than predicted from the theoretical analysis.

Back pressure independent flow conditions were investigated for values of  $P_{s0}/P_{p0}$  in the approximate range:  $.048 \leq P_{s0}/P_{p0} \leq .180$ . The mixing

duct static pressure distribution was used to insure that the ejector flow was in the supersonic flow regime. The pressures:  $P_{p1}$ ,  $P_{s1}$ ,  $P_{s0}$ ,  $P_{m3}$ , and the mixing duct static pressure distribution were recorded by photographing the manometer board. A precision pressure gage was used to measure the primary and exit plane stagnation pressures. The necessary VDI nozzle data were also recorded to determine the mass flowrates. This entire set of experiments was conducted for mixing ducts with length-to-width ratios,  $L/W = 9.0, 13.0$ , and  $16.374$ .

Static pressure measurements versus time were recorded to establish approximately the intensity and scale of the turbulence within the mixing duct. As a result of the unexpected nature of these preliminary transient measurements, a series of experiments was conducted following the procedures planned for the periodic driver flow experiments. The static pressures were recorded simultaneously at pressure taps on the primary flow centerline and on the subsonic secondary flow wall along the length of the mixing duct. These data sets were recorded at values of  $P_{s0}/P_{p0} = .070$  and  $.160$  in the  $L/W = 13.0$  mixing duct and at values of  $P_{s0}/P_{p0} = .100$  and  $.160$  in the  $L/W = 9.0$  mixing duct. The exit plane stagnation pressures were also recorded. Static pressures within both the  $L/W = 13$  and  $9$  mixing ducts at  $P_{s0}/P_{p0} = .070, .100, .130$ , and  $.160$  were examined on an oscilloscope display which was triggered by the Biomation. The mixing duct flow was examined at several duct locations for side to side symmetry. The secondary stagnation pressure,  $P_{s0}$ , was examined for steadiness.

Most of the experiments were conducted in the mixed regime near the experimental break-off point with the supersonic regime. This was done

because the ejector flow began to break-off from SR flow at values of  $P_{m3}/P_{s0}$  that were significantly lower than the theoretically predicted values and because the sharp theoretical break-off between SR and MR flows and the rapid decrease of  $M_{s1}$  in the mixed regime, as shown in Fig. 2.1-2, experimentally were found to be a smoother transition followed by a more gradual decline of  $M_{s1}$  and  $w_{sp}$ . Thus, truly back pressure independent SR flow mass flowrate ratios, which were obtained at the sacrifice of pressure recovery, were not significantly greater than MR flow values obtained at higher  $P_{m3}/P_{s0}$ . MR flow near break-off was examined in order to obtain a more complete picture of ejector performance.

Another set of experiments was conducted for values of  $P_{s0}/P_{p0} = .070, .100, .130, \text{ and } .160$  with  $L/W = 9.0$  mixing duct to determine how the mass flowrate ratio decreased as  $P_{m3}/P_{s0}$  was increased above the break-off value. The exit plane static pressure,  $P_{m3}$ , was digitally recorded and then averaged to determine an effective value of  $P_{m3}/P_{s0}$ . In all other respects the experimental procedure was the same as that used in the preliminary runs discussed at the beginning of this section; however, the number of experiments conducted was more extensive.

### 3.2.2 Periodic Flow Experimental Procedure

Periodic driver flow ejector experiments were conducted at driver frequencies of 142 Hz and 250 Hz. More experiments were conducted with the  $L/W = 9.0$  mixing duct than the two longer ducts because it was desired to determine whether or not ejector performance with a shorter mixing duct could be improved by a periodic driver. The mixing duct with

$L/W = 16.374$  duct was only investigated for the back pressure independent mass flowrate ratios with the 142 Hz driver.

Preliminary experiments were conducted to correlate the stagnation pressure upstream of the oscillator inlet to the mean value,  $\overline{P_{p0}}$ , of the stagnation pressure in the resonance chamber of the oscillator slightly upstream of the ejector primary inlet. With this correlation,  $\overline{P_{p0}}$  could accurately be set by adjusting the steady oscillator inlet stagnation pressure. This correlation was found to be constant within .5% over the range of pressures of interest and repeatable within calibration accuracy.  $\overline{P_{p0}}$  was approximately 90% of the oscillator inlet stagnation pressure at both driver frequencies. It is through this correlation procedure that a representative or effective value of  $P_{s0}/P_{p0}$  is obtained for comparison of periodic and steady driver ejector flow results.

The use of an overbar to indicate the mean will be dropped with the mean value being understood. Proper reference to time is made for instantaneous values.

The procedures outlined for the steady flow experiments using the electronic data sampling equipment were followed. This includes static pressure measurements along the length of the ducts and mass flowrate break-off experiments. These procedures were repeated completely with the 142 Hz driver; for the 250 Hz driver flow, experiments were conducted with only a mixing duct with  $L/W = 9.0$ .

Experiments were run at both driver frequencies measuring  $P_{p0}$ ,  $P_{p1}$ , and  $P_{s1}$  simultaneously over the range of  $P_{s0}/P_{p0}$ . This was done so that the ratios  $P_{s1}/P_{p1}$  and  $P_{p1}/P_{p0}$  could be observed with time.  $P_{p1}$  could

also be compared with  $P_{p0}$  to determine how oscillator pressure pulses may have been altered by passage through the C-D nozzle at the primary flow inlet.

### 3.3 EXPERIMENTAL RESULTS

Steady driver ejector flow performance parameters have been compared, in the following discussion, with the one-dimensional theory and with periodic driver ejector flow performance parameters. The comparison with theory has been done to identify trends in ejector performance over the range of flow conditions and mixing duct lengths and to test the theory. The quasi-steady analysis cannot be expected to predict periodic driver ejector flow conditions better than the one-dimensional analysis predicts steady driver ejector flow conditions. The effects of a periodic driver on ejector flows are judged by the comparisons made with steady driver ejector flows and with the predictions of the *quasi-steady analysis*.

#### 3.3.1 Steady Flow Experimental Results

The back pressure independent performance parameters of the steady flow ejector were found to follow closely the trends predicted by the one-dimensional analysis with the exception of the back pressure ratio,  $P_{m3}/P_{s0}$ , at the break-off point. In Fig. 3.3.1-1, it can be seen that the experimental and theoretical values of  $P_{s1}/P_{p1}$  agree reasonably well. The value of  $M_{p1}$  used in the theoretical analysis was determined experimentally from  $P_{p1}/P_{p0}$  and the isentropic relations [43]. The two longer mixing ducts produced values of  $P_{s1}/P_{p1}$  which were consistently below the theoretical curve; the shortest mixing duct produced values

which were slightly above the theoretical curve. This suggests that  $M_{s,1}$  and  $w_{s,p}$  should be smaller for the shorter duct. Figure 3.3.1-2 does indicate that lower  $w_{s,p}$  values occurred with the shorter  $L/W = 9.0$  duct over most of the range of  $P_{s,0}/P_{t,0}$ . However, the mass flowrate characteristics of the shortest mixing duct do not follow the theoretical curve as well as the two longer ducts, the experimental results are below and above the theoretical curve. It was also observed that the shorter duct had to be operated at lower back pressure conditions before performance parameters began to level off as supersonic regime back pressure independence was approached. The back pressure ratio,  $P_{m3}/P_{s,0}$ , for each of the experiments are indicated in Fig. 3.3.1-3. It did seem that lower values of  $P_{m3}/P_{s,0}$  might have further improved the shortest duct mass flowrate performance, however, this would have been at the sacrifice of the resulting ejector pressure recovery. This matter was not pursued because mixed flow static-to-stagnation pressure ratios in the exit plane,  $P_{m3}/P_{m0}$ , below the sonic flow value, .528, were obtained.

During the course of the steady flow experiments, the static pressure profiles observed in all three mixing ducts changed dramatically with the back pressure ratio,  $P_{m3}/P_{s,0}$ . At back pressures lower than the SR flow break-off value, the static pressure decreased smoothly on the subsonic flow wall and along the primary flow centerline as both secondary and primary flows accelerated after entering the mixing duct. The flow would remain at these low pressure levels to within four duct widths of the exit plane; a rapid pressure rise to the exit plane condition would take place in the remainder of the duct. As  $P_{m3}/P_{s,0}$  was increased, the

distance downstream in the duct that the flow would remain in a low pressure, high velocity state decreased. The value of  $P_{m3}/P_{s0}$  at which the initial pressure decrease and the corresponding acceleration was immediately followed by the onset of the pressure recovery process was approximately the break-off value of  $P_{m3}/P_{s0}$ . A decrease in the mass flow-rate ratio was always observed to occur as  $P_{m3}/P_{s0}$  was further increased for a given value of  $P_{s0}/P_{p0}$  in the  $L/W = 13.0$  and  $L/W = 16.374$  mixing ducts. Thus, break-off from SR to MR flow had occurred. As  $P_{m3}/P_{s0}$  was further increased the shock structure in the supersonic core became stronger, particularly at lower values of  $P_{s0}/P_{p0}$ . Although the primary flow expanded and accelerated to low pressures as it did at lower values of  $P_{m3}/P_{s0}$ , the secondary flow was accelerated less as indicated by the smaller pressure drop along the wall downstream of the entrance of the duct, Station 1. As  $P_{m3}/P_{s0}$  was increased further, secondary flow wall pressures in the acceleration section of the duct remained constant and equal to  $P_{s1}$ . At this value of  $P_{m3}/P_{s0}$ , the mass flowrate ratio had probably decreased by approximately 50% from the SR flow value.

The important features of the mixing duct static pressure profile are demonstrated in Fig. 3.3.1-4. Pressure taps along the subsonic secondary flow walls are referred to as being at the wall and pressure taps on the primary flow centerline are referred to as being at the center in all of the following discussions and in all figures. The wall and center tap static pressures along the length of the  $L/W = 16.374$  mixing duct are presented in Fig. 3.3.1-4 for two steady flows with, as near as possible, the same value of  $P_{s0}/P_{p0}$ . Although the difference between the two profiles

is significant, the profile for the lower value of  $P_{m3}/P_{s0}$  was obtained by increasing the value of  $P_{p0}$  above that of the other profile from 71.22 psia to 73.80 psia and adjusting  $P_{s0}$  accordingly. With a periodic driver, the reverse case was found, i.e., the value of  $P_{m3}/P_{s0}$  is approximately constant while  $P_{s0}/P_{p0}$  changes; however, the effects on the mixing duct pressure profile are still the same. At these pressure levels, the oscillator pulses have a total amplitude of 12 to 15.25 psi. Using the theoretical results as a guide, the effective changes in the break-off value of  $P_{m3}/P_{s0}$  should be larger than the difference between the two values shown in Fig. 3.3.1-4 at the same value of  $P_{s0}/P_{p0}$ .

### 3.3.2 Periodic Flow Experimental Results

During the experiments with the steady and periodic driver flows, three types of unsteady flow phenomena were observed in the mixing duct flow. The largest disturbances found within the mixing duct appear to be due to changes in and motion of the shock structure in the supersonic core. These shock waves and their location seemed quite unstable, which may have been due to other unsteady disturbances. A low amplitude oscillation of the static pressures within the duct with frequencies up to approximately 1000 Hz was also observed. This oscillation was more noticeable in the mixing duct with  $L/W = 9.0$  than with  $L/W = 13.0$ . These oscillations were present in the wall or secondary flow at Station 1 but if observed, were not seen in the center flow until after  $X/W = 1.0$ . Oscillation amplitudes usually increased in the acceleration section of the mixing duct; however, low back pressure conditions were found to

inhibit this growth and to diminish the amplitudes at Station 1. The most surprising phenomena found with either steady or periodic driver flows are shown in Fig. 3.3.2-1. Large amplitude pulses, sometimes bursting into periodic groups, were observed in most flows. These pulses originated in the wall flow at approximately the end of the acceleration section of the flow which is near the location of the first shocks embedded in the center flow. The amplitude and frequency of occurrence of these bursts increased as  $P_{s0}/P_{p0}$  decreased. In many cases these bursts appear to have been an amplification of the smaller amplitude pulses mentioned above. Neither the origin or amplification of these disturbances is well understood. Changes in operating conditions which adversely increased the secondary flow pressure gradient through the duct and increased the strength of the shocks in the supersonic core are believed to stimulate these pulses. It appears that corner flow separation and reattachments, shear layer instabilities, and disturbances due to the unstable shock structure which propagate into the subsonic wall flow are probable mechanisms for these unsteady phenomena. Investigations of unsteady turbulent boundary layers have found bursts in intensity levels do occur in some cases with periodic freestream flows [44,45]. The turbulence at the edge of the boundary layer can "violently" increase in level and burst into the freestream flow. Oscillations in the shock structure of the supersonic core may be coupled with larger scale turbulence to stimulate such bursts. Figure 3.3.2-2 shows one more feature of all pulses, that is side-to-side symmetry was always found in all flows.

A set of static pressure profile data taken along the length of the mixing duct with  $L/W = 9.0$  and with  $P_{s0}/P_{p0} = .100$  for steady and both periodic driver flows is included in Figs. 3.3.2-3 to 3.3.2-21 to present a clear picture of what occurs within the mixing duct and how some of the many variables affect the flow. All data was taken for steady, 142 Hz, and 250 Hz driver flows with approximately equivalent input and back pressure flow conditions. Figures 3.3.2-3 and 3.3.2-4 are the primary and secondary static pressures at Station 1 versus time for both periodic driver frequencies. The secondary flow pulses are somewhat irregular and the periodicity appears to be much weaker at the lower frequency. These irregular oscillations in the secondary flow were not as large in the mixing duct with  $L/W = 13.0$ . The oscillations in the secondary flow have grown by  $X/W = 0.333$  and are prominent with both steady and periodic driver flows; these data are shown in Figs. 3.3.2-5, 3.3.2-6, and 3.3.2-7. Note that the center flow has not been affected by the irregular disturbances observed in the subsonic wall flow. Also, note that the 250 Hz wall flow pulses slightly precede those in flow at the center. This phase shift can be seen in nearly all of the data taken in the first 1/3 of the mixing duct; it was usually more noticeable with the 250 Hz driver flow. Static pressures continue to drop as the flows interact and accelerate until somewhere near  $X/W = 1.0$ . Shocks occur in the primary flow where it stops expanding against the secondary and readjusts its flow direction. Disturbances that occur in the wall flow also appear in the center flow at  $X/W = 1.0$ , see Figs. 3.3.2-8, 3.3.2-9, and 3.3.2-10. The periodicity of the center flow seems to fade in and out. The pulses at  $X/W = 1.0$  in the

expanded 142 Hz driver ejector flow are larger and steeper than could be produced solely by driver flow pulsations. Figure 3.3.2-11 is an example of how much the driver pulses were diminished by the expansion of the supersonic primary flow. The data in this figure were taken for a back pressure independent SR flow experiment with  $P_{s0}/P_{p0} \approx .070$ . The  $P_{s0}/P_{p0} = .100$  data under consideration has a back pressure sufficiently high for the mass flowrate ratio to have decreased about 9% from the back pressure independent SR flow value. Shock waves, due to the relatively high back pressure, are present in this MR flow and their unsteady behavior in the periodic flow is believed to be the cause of the larger pulses in the flow at  $X/W = 1.0$ . As mentioned earlier, the strength and in most cases the number of shocks in the flow increase when SR flow breaks-off to MR flow due to an increase in  $P_{ns}/P_{s0}$ . Note also that the unsteadiness of the shock waves in the steady driver ejector flow is comparable to the periodic driver ejector flows. Shock waves are clearly present at the  $X/W = 1.333$  pressure tap location, as shown in Figs. 3.3.2-12, 3.3.2-13, and 3.3.2-14. The smaller oscillations at the subsonic wall flow pressure taps are similar in appearance to the large oscillations at the center taps and are phase-shifted slightly ahead of the disturbances at the center. The periodic driver moves the shock waves upstream and downstream within the mixing duct; some of these shock waves may disappear or coalesce and then reappear. The shock waves in the steady driver ejector flow are quite unsteady; however, their unsteady action is intermittent and not as vigorous as in the periodic driver flows. The shock wave patterns are the dominant feature within the flow in the mixing duct until

$X/W = 6.0$ ; however, at  $X/W = 4.0$ , the wall flow appears to be decoupled from the action in the primary flow at the center. These mixing duct flow features are shown in Figs. 3.3.2-15, 3.3.2-16, and 3.3.2-17. The 250 Hz driver flow again appears more pulsatile than the 142 Hz driver flow. The static pressure levels at  $X/W = 4.0$  have not increased significantly since  $X/W = 1.333$  and the flow does not appear to have mixed significantly either. Shock waves are present in the flow downstream of  $X/W = 6.0$  but are not evident at  $X/W = 8.0$ . At  $X/W = 8.0$ , the center and wall flows have become noticeably more broken and turbulent. The mixing duct flow is significantly more uniform across the duct; the mixing duct flow at this location is essentially the same for all three of the driver flows, see Figs. 3.3.2-18, 3.3.2-19, and 3.3.2-20. The 142 Hz driver ejector flow is weakly periodic at  $X/W = 8.0$  while the 250 Hz driver ejector flow is definitely periodic. The supersonic core flow seems to have finally disintegrated in all three driver flows between  $X/W = 6.0$  and  $X/W = 8.0$ , thus initiating a rapid mixing and pressure recovery process. This rapid mixing, which occurred immediately downstream of the disappearance of the supersonic core, was also noticed in water table studies of supersonic-subsonic ejector flow where dye was injected into the wall flow to indicate mixing rates. At the exit plane, all three driver ejector flows are nearly identical. Periodicity was still weakly present at the exit plane of the mixing duct due to the muffler and back pressure valve flow resistance; this is shown in Fig. 3.3.2-21. It should be noted that the mean static pressure levels at most locations in the mixing duct are approximately the same for all three driver flows. As shown in Figs. 3.3.2-22 and 3.3.2-23, the exit

plane stagnation pressures were nearly indistinguishable and periodicity was not a strong feature.

The only notable difference between the steady and periodic driver ejector flows in the mixed regime flows discussed above was the increased activity of the shock waves in the supersonic primary flow. Supersonic regime flows operating at the same  $P_{s0}/P_{p0}$  as a mixed regime flow had fewer and weaker shocks than the mixed regime flow. Thus, supersonic regime flows were less susceptible to disturbances due to a periodic driver flow than mixed regime flows.

The primary-to-secondary stagnation pressure ratio had a pronounced effect on mixing duct flow features. Lower values of the stagnation pressure ratio tended to have strong shock waves within the flow for all but the low back pressure SR flows. The experimental data with  $P_{s0}/P_{p0} = .100$  that was just discussed is typical.

The opposite case is true for higher values of  $P_{s0}/P_{p0}$ . For  $P_{s0}/P_{p0} = .160$ , the resultant  $P_{s1}/P_{p1}$  is roughly .9. In this case the primary flow does not expand as much after entering the mixing duct as it did at the lower values of  $P_{s0}/P_{p0}$ ; consequently, the resulting shock waves in the supersonic core flow do not have as great an effect on the flow. Static pressure measurements were taken in the  $L/W = 9.0$  mixing duct with  $P_{s0}/P_{p0} = .160$  and a back pressure ratio sufficiently high to have caused the mass flowrate ratio to decrease by approximately 8% from the back pressure independent value. The largest disturbances within this flow are shown in Figs. 3.3.2-24, 3.3.2-25, and 3.3.2-26. The pulses in the periodic flow were probably due to a weak shock wave moving and/or

changing in strength. This was the only location where disturbances of any notable size were found. The static pressures at Station 1 for  $P_{s0}/P_{p0} = .160$  and the  $L/W = 9.0$  mixing duct and for  $P_{s0}/P_{p0} = .070$  and the  $L/W = 13.0$  mixing duct are shown in Figs. 3.3.2-27 and 3.3.2-28 respectively. From these figures, the secondary flow pulses are seen to decrease appreciably with  $P_{s0}/P_{p0}$ .

Experimental values of  $P_{s1}/P_{p1}$  versus time were compared with values determined from the theoretical quasi-steady analysis. Obtaining the  $P_{s0}/P_{p0}$  versus time data as required for the theoretical analysis was not as straightforward as was initially expected. Figures 3.3.2-29 and 3.3.2-30 are the simultaneously recorded primary stagnation and static pressures for the 142 Hz and 250 Hz drivers, respectively. The stagnation pressure probe was located immediately upstream of the primary C-D nozzle inlet and the static tap was located at the center of the nozzle exit plane, Station 1. The separation distance between these two locations led to the small phase shift seen in both figures. The 250 Hz driver flow stagnation pressure profile was pressure invariant. The higher frequency components in the 142 Hz driver flow profiles grew slightly in amplitude, relative to that of the base frequency, as the mean pressure level increased. Difficulties were encountered when examining the variation of  $P_{p1}/P_{p0}$  with time. The decision was made to phase-shift  $P_{p1}$  with respect to  $P_{p0}$  such that the relatively sharp valleys of each cycle were in phase before determining  $P_{p1}/P_{p0}$  as a function of time.  $P_{p1}/P_{p0}$  was found to be oscillatory and to be affected strongly by the higher frequency components of  $P_{p0}$  which were not present in  $P_{p1}$ ; this is shown in

Figs. 3.3.2-31 and 3.3.2-32. Note that for the 250 Hz driver flow, the  $P_{p1}/P_{p0}$  curve was determined from a different set of data than was used in Fig. 3.3.2-30; both sets of data were in phase with one another and the pressure difference between the two was not large. The same data was used to determine both 142 Hz plots. The ratio,  $P_{p1}/P_{p0}$ , for the 250 Hz driver flow was at a minimum when  $P_{p0}$  was at a maximum but the 142 Hz data seems to indicate just the opposite. The mean values of  $P_{p1}/P_{p0}$  at both driver frequencies was approximately constant at a value of  $P_{p1}/P_{p0} = .140$  as compared to the steady flow value of  $P_{p1}/P_{p0} = .136$ . The pulsed flow in the resonance chamber of the oscillator adjusts, by wave action, to the area change between the resonance chamber and C-D nozzle throat as well as the choked flow condition at the nozzle throat [46]. This wave action adjustment of the flow apparently has altered the wave form of the pressure pulses between the stagnation probe and Station 1 as indicated in Figs. 3.3.2-29 and 3.3.2-30. In order to obtain  $P_{s0}/P_{p0}$  versus time for the theoretical analysis, values of  $P_{p1}$  were recorded and divided by the mean value of  $P_{p1}/P_{p0}$  at the given pressure conditions to determine  $P_{p0}$  versus time.  $P_{s0}$  was held constant and  $P_{s1}$ ,  $P_{p1}$ , and  $P_{p0}$  were all simultaneously measured. The agreement between experimental and theoretical results is reasonably good; these comparisons are in Fig. 3.3.2-33. The experimental data with a mean value of  $P_{s1}/P_{p1} = .504$  was taken for a flow in the mixed regime with the back pressure sufficiently high to have caused an 8% decrease in the mass flowrate ratio from the supersonic regime value. Thus,  $M_{s1}$  and  $w_s/w_p$  are less than the break-off value while  $P_{s1}/P_{p1}$  is greater. The data with a mean value of  $P_{s1}/P_{p1} = .656$  was taken for a flow

in the supersonic regime while the data with a mean value of  $P_{s1}/P_{p1} = .875$  was taken for a flow in the mixed regime with a mass flowrate 3 to 4% less than the break-off value. The value of the primary nozzle exit Mach number used in the analysis was  $M_{p1} = 1.957$ , the same value as was used in the steady flow analysis.

The imposed back pressure had other effects on the performance of the ejector than those previously described. Depending on the back pressure, the ejector exit plane stagnation pressures were found to differ between the wall and center probe locations by as much as a factor of two or by very little. Lower back pressures and the shortest mixing duct produced the most non-uniform flow at the ejector exit plane. The periodic driver flow had little effect on the exit plane stagnation pressure uniformity. The mean value of the center and wall stagnation pressures were more nearly equal for some periodic flows that were near the break-off back pressure ratio. However, results were inconsistent. The ratio,  $P_{s0}/P_{p0}$ , seemed to have an effect and  $P_{ns}/P_{s0}$  itself produced a uniform exit plane flow if it was sufficiently high.

As was mentioned earlier, SR ejector flows at low back pressures remained in a low pressure high velocity state, free of shock waves of noticeable strength, to within four duct widths of the exit plane. It was observed that under these flow conditions the wall and center pressure pulses were shifted completely out of phase downstream of the initial acceleration section of the mixing duct; this is shown in Fig. 3.3.2-34. An expansion of the supersonic primary flow, as indicated by a pressure drop at the center pressure tap, caused a deceleration and pressure rise

in the secondary flow at the wall pressure tap. Thus, it appears that after choking the secondary flow accelerates to a supersonic flow if the primary contracts slightly due to shock waves imbedded in the supersonic core. Nelson [47] found that normal shock waves occurred in the wall flow of a similar two-dimensional constant area supersonic-subsonic ejector.

The way that the mass flowrate ratio declines when an SR flow breaks-off to MR flow due to an increase in  $P_{m3}/P_{s0}$  was found to differ for steady, 142 Hz, and 250 Hz driver flows at most values of  $P_{s0}/P_{p0}$  which were examined. It was observed that the back pressure independent SR mass flowrate ratios were approximately the same for all three driver flows but that the MR flow mass flowrate ratios at a given back pressure ratio,  $P_{m3}/P_{s0}$ , were higher with the periodic drivers than with the steady driver. Figures 3.3.2-35, 3.3.2-36, and 3.3.2-37 show these mass flowrate trends. It appears that the periodic driver ejector flows break-off at higher  $P_{m3}/P_{s0}$  than the steady driver ejector flows. The maximum difference between the values of  $P_{m3}/P_{s0}$  at a given  $P_{s0}/P_{p0}$  and the  $w_s/w_p$  occurs between the steady and 250 Hz driver ejector flows at  $P_{s0}/P_{p0} = .070$ ; this difference is less than 5%. The 142 Hz driver did not differ from the steady driver by a significant amount in most cases and all three driver ejector flows followed the same break-off trends at  $P_{s0}/P_{p0} = .160$ .

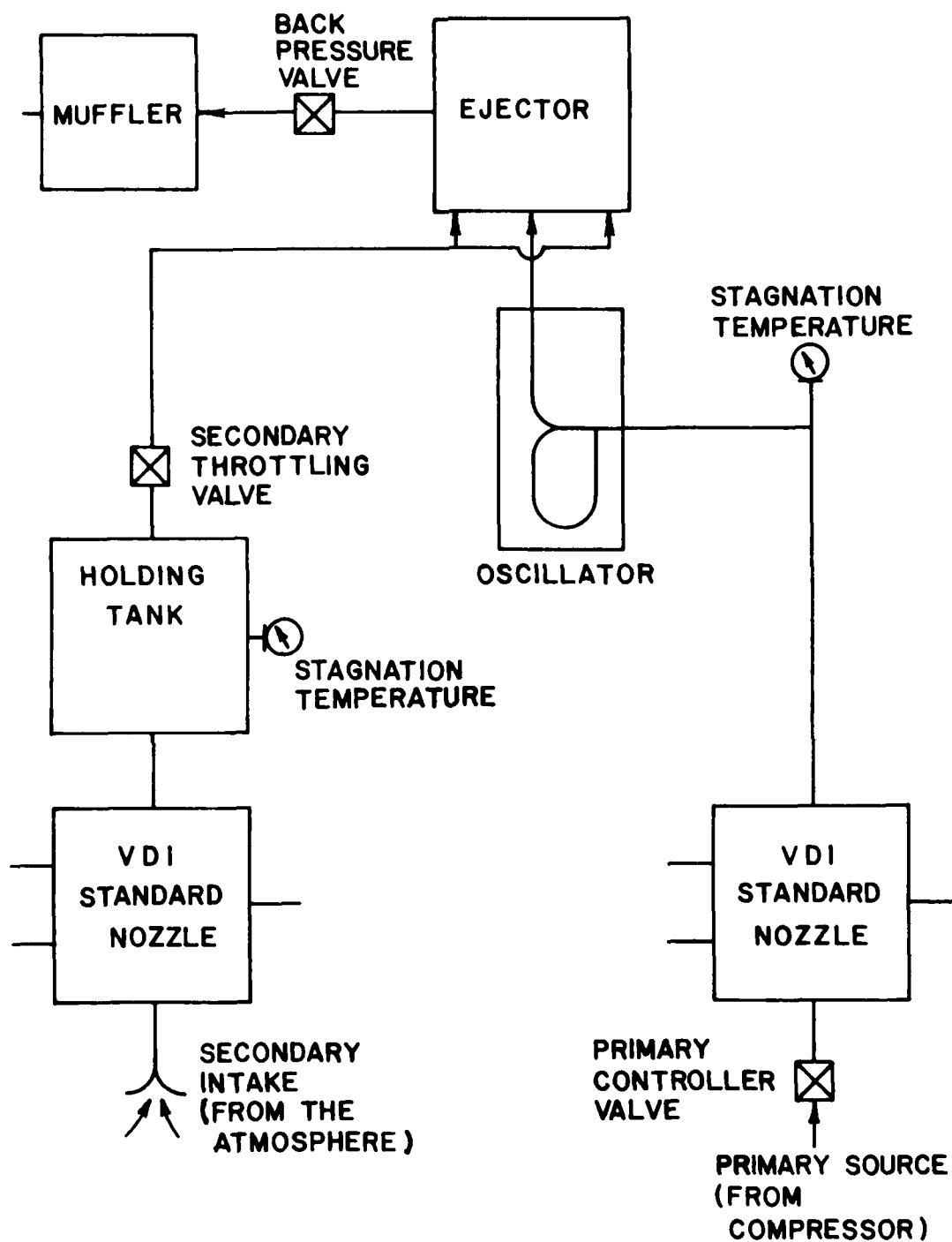


Figure 3.1-1 Flow schematic of the test rig



Figure 3.1-2 The fully assembled ejector unit ( $L/W = 9.0$ )

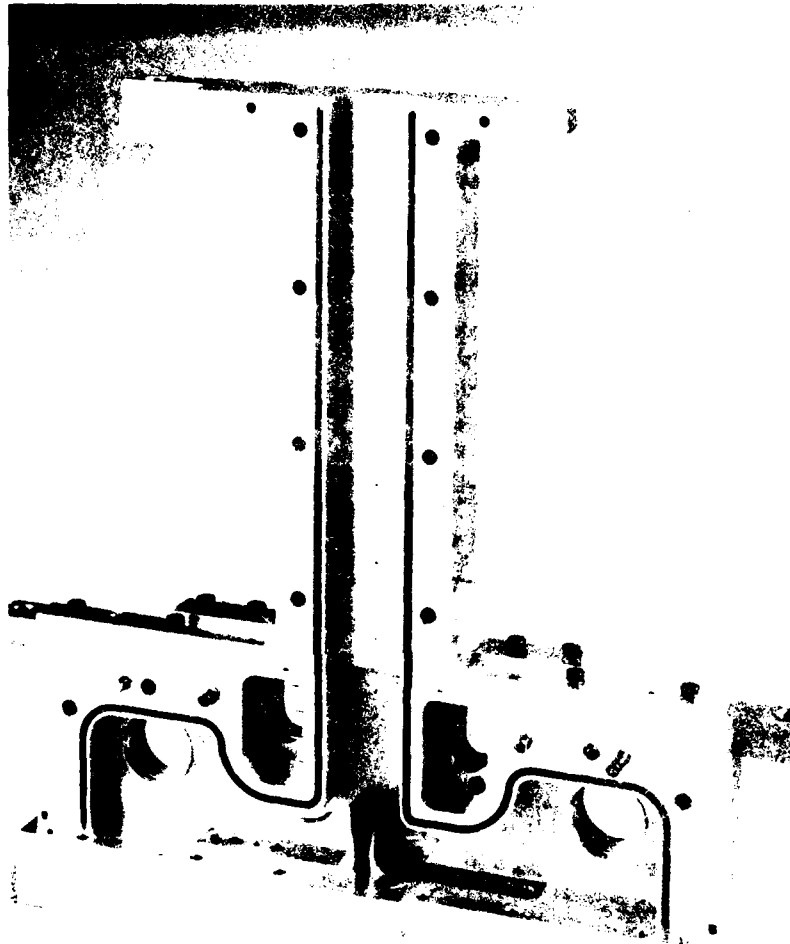


Figure 3.1-3 The partially assembled ejector unit (L/W = 9.0)

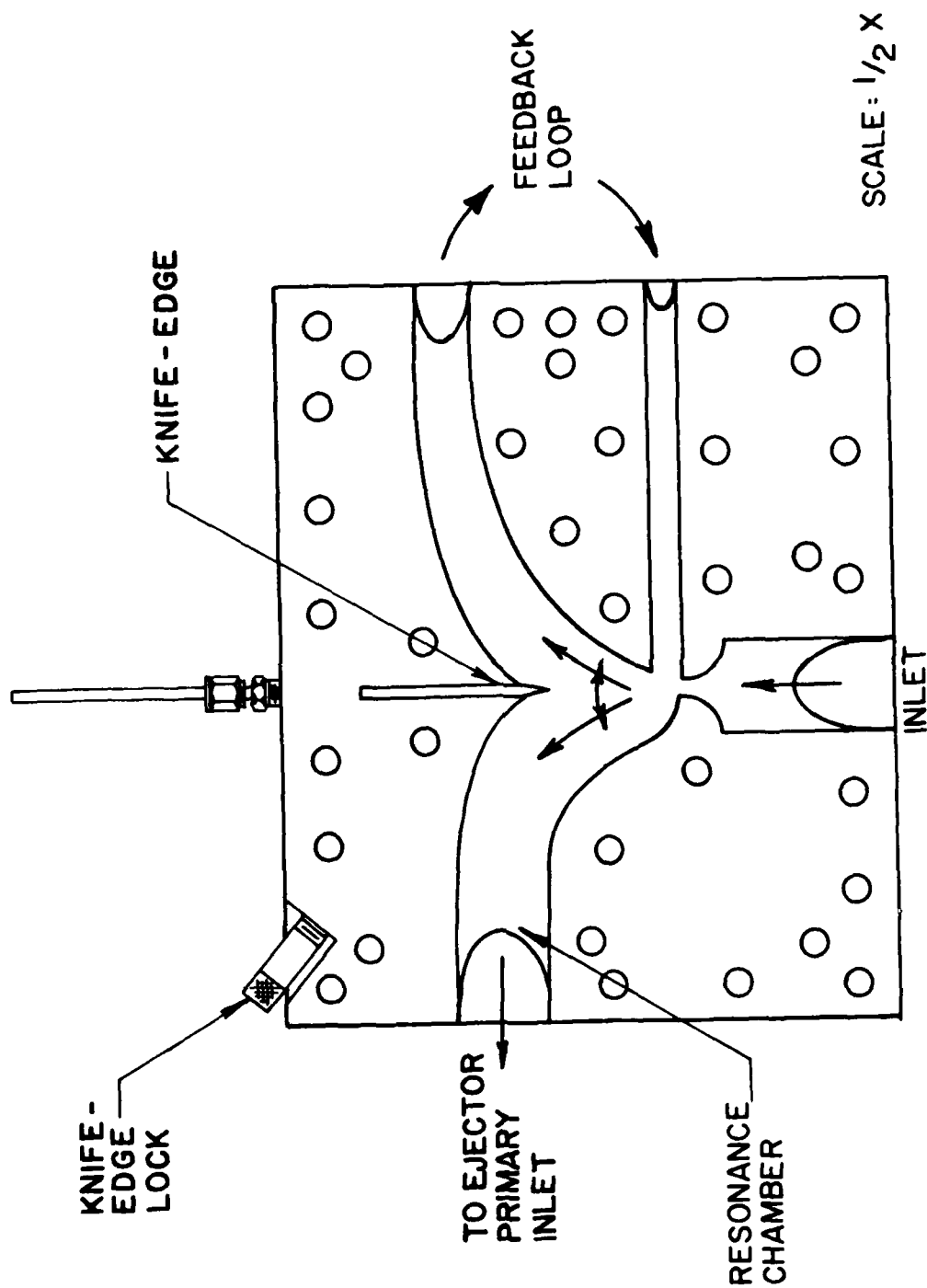


Figure 3.1-4 View of the partially assembled oscillator body

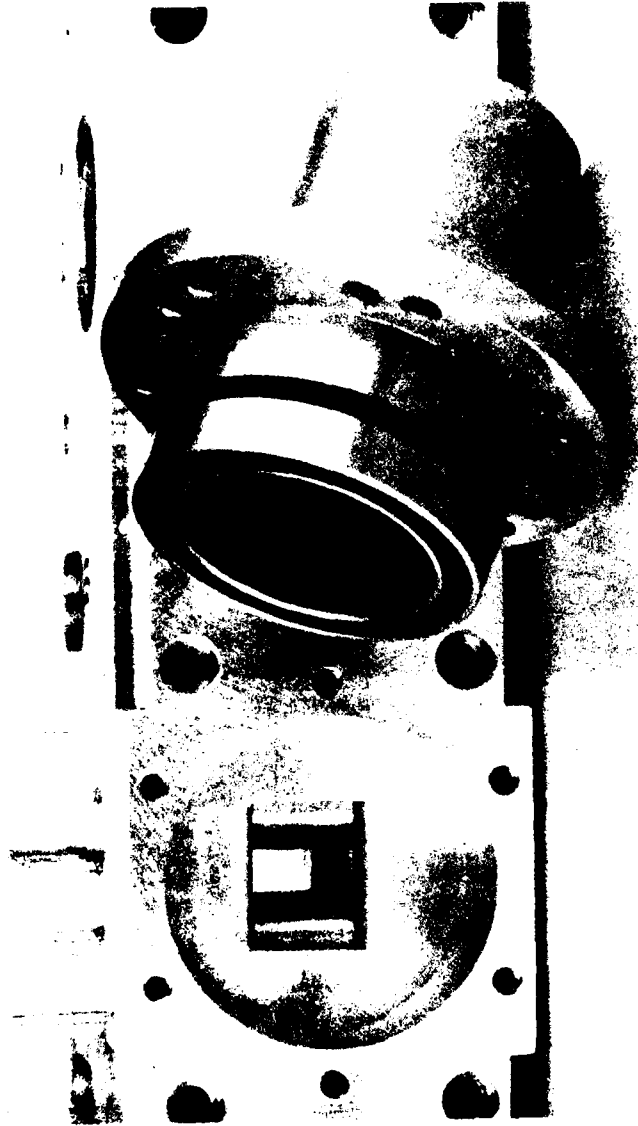


Figure 3.1-5 View of the primary flow inlet to the ejector

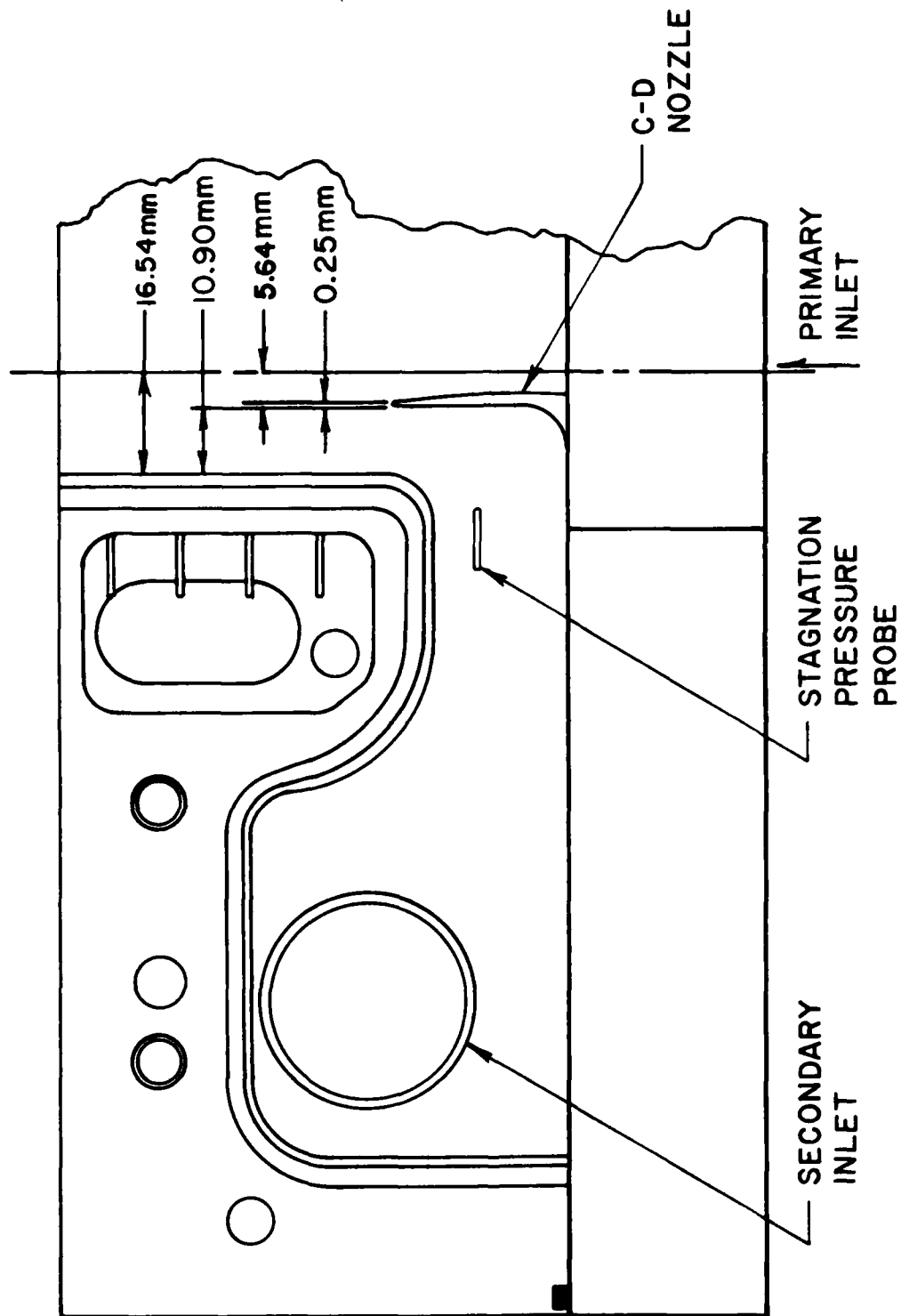


Figure 3.1-6 View of the partially assembled ejector base piece

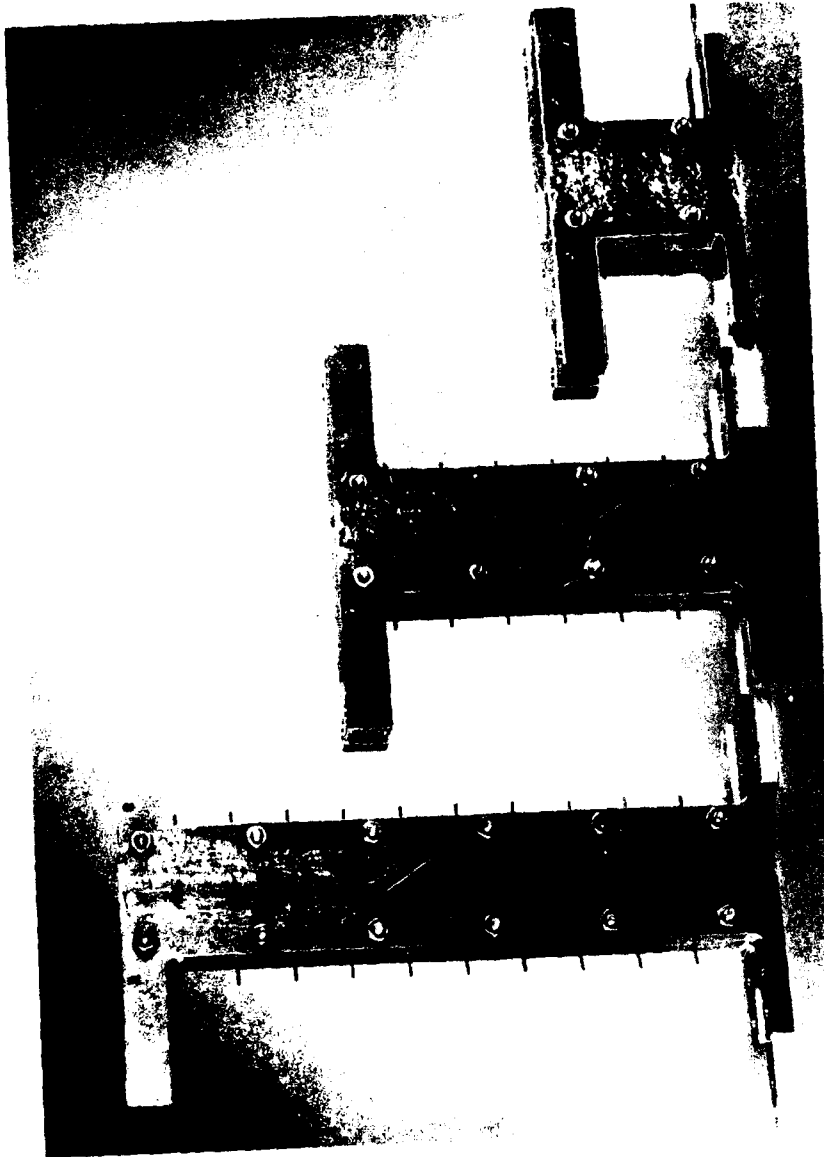


Figure 3.1-7 View of the ejector mixing duct assemblies

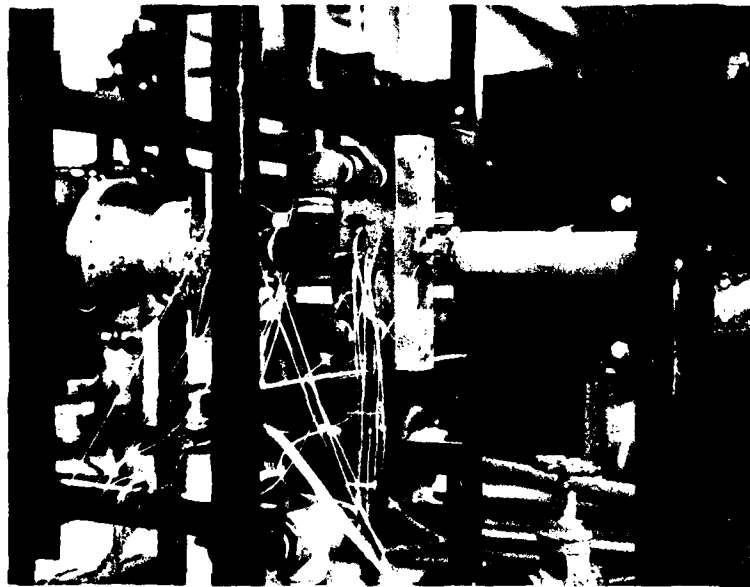


Figure 3.1-8 View of the secondary and primary lines connected to the base assembly



Figure 3.1-9 View of the test rig

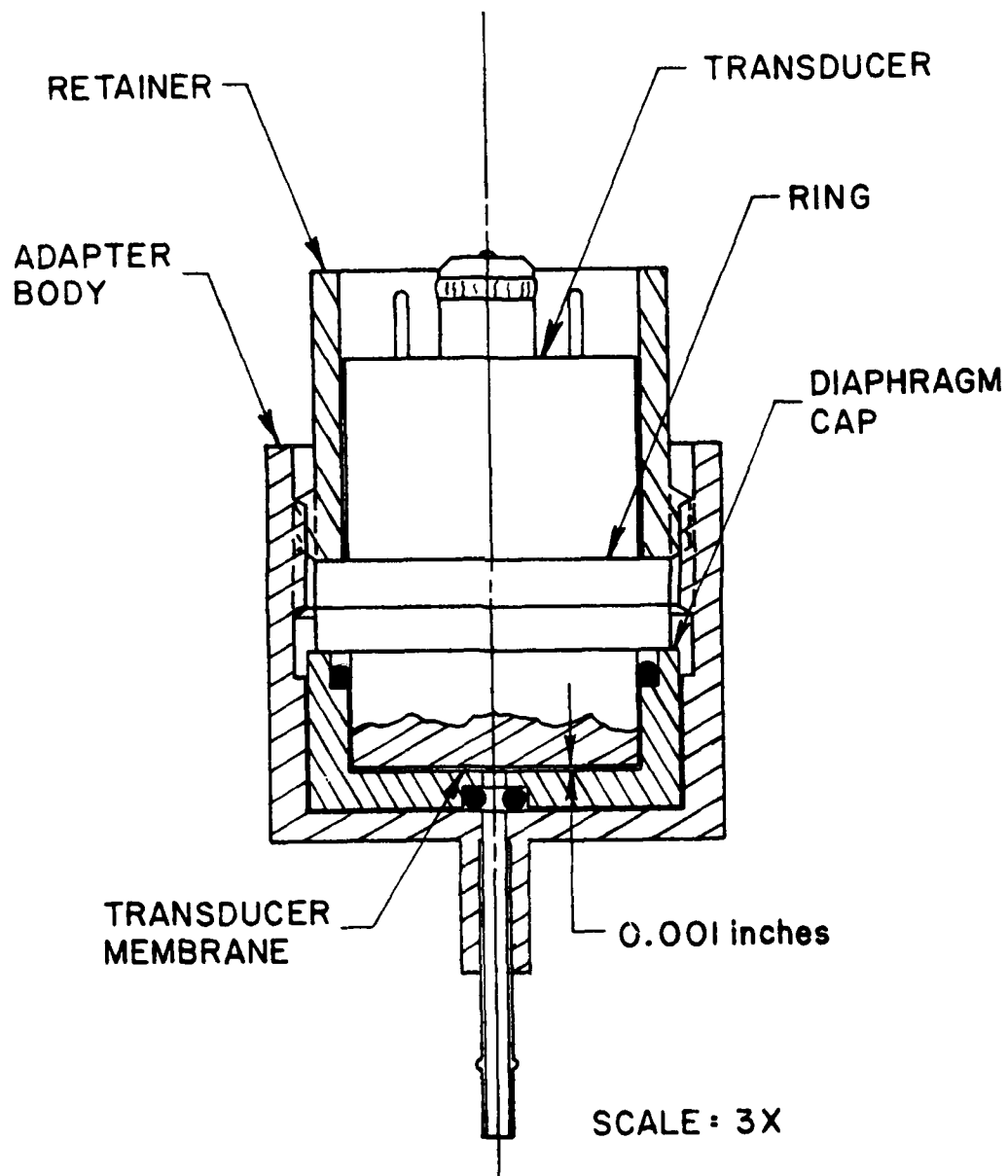


Figure 3.1-10 Cross-sectional view of the Scanivalve "zero" volume line adapter with a CEC type 4-312 pressure transducer in place

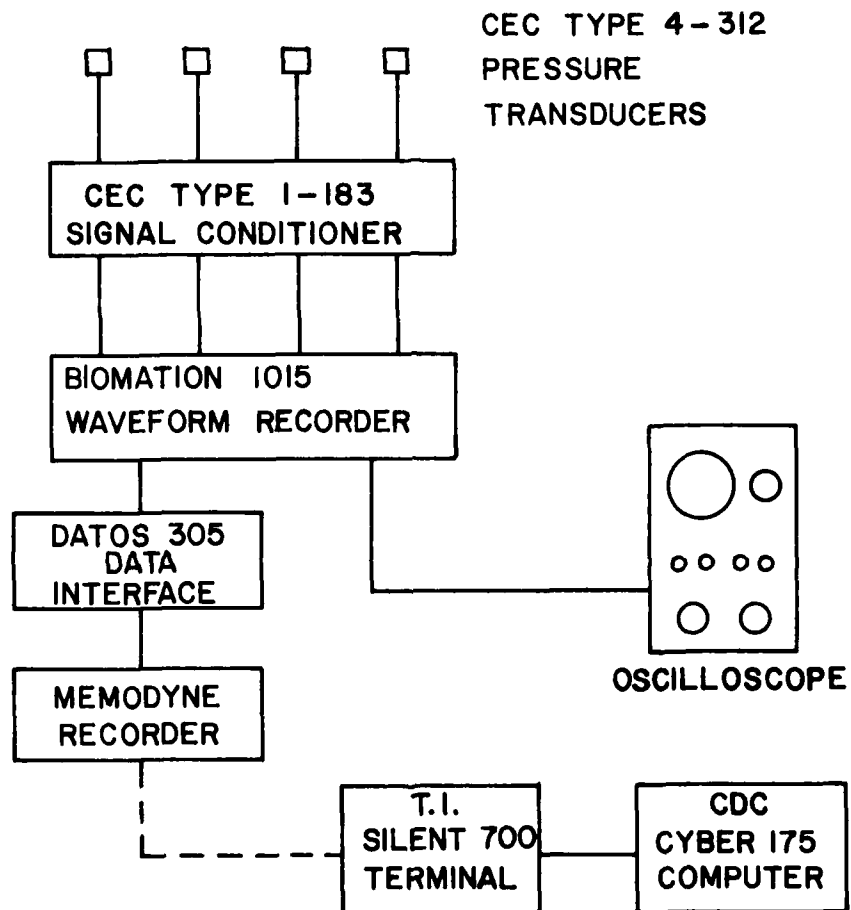


Figure 3.1-11 Schematic detailing the data acquisition system

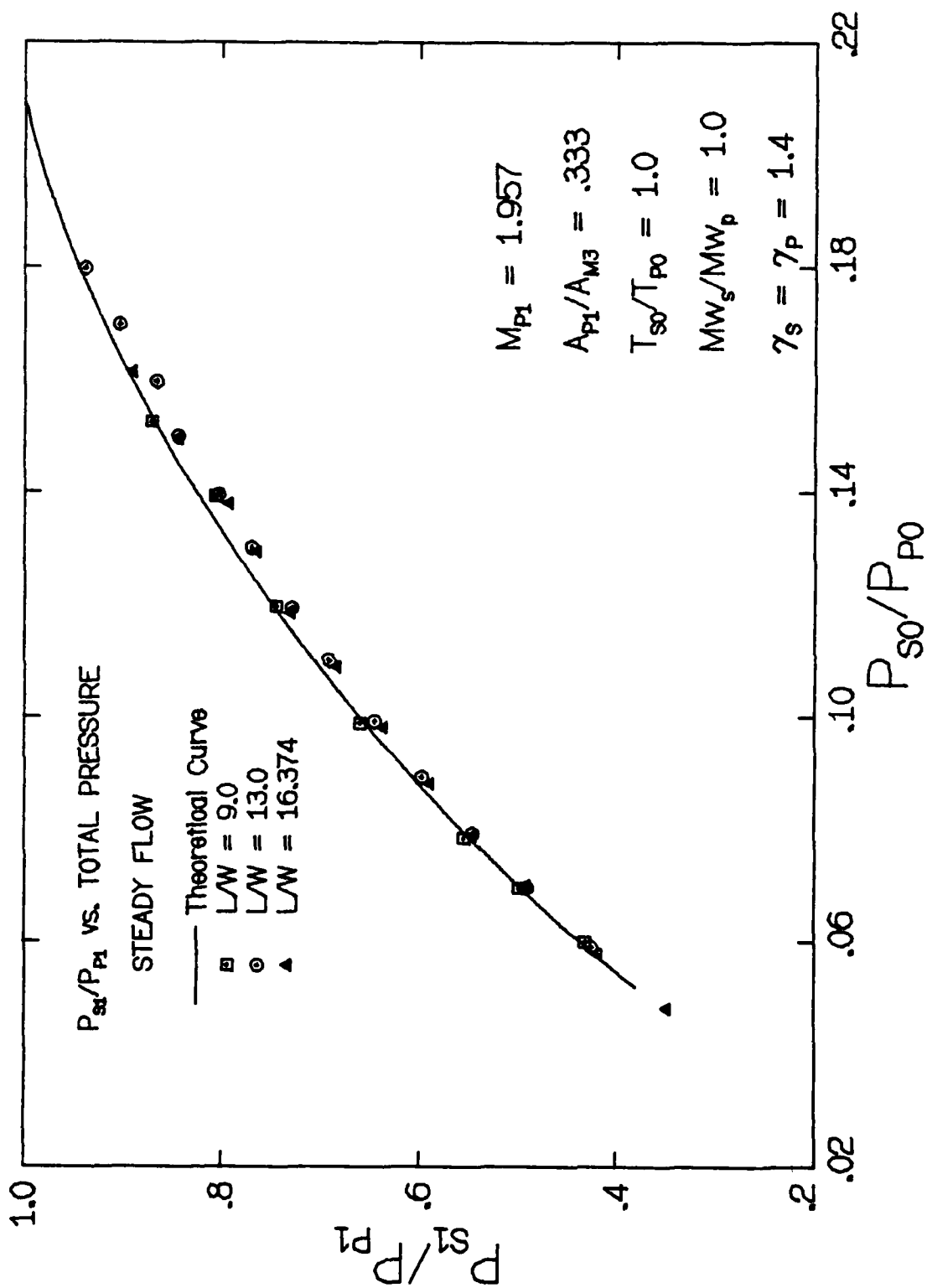


Figure 3.3.1-1 Back pressure independent steady flow values of  $P_{s1}/P_{p1}$  versus  $P_{s0}/P_{p0}$

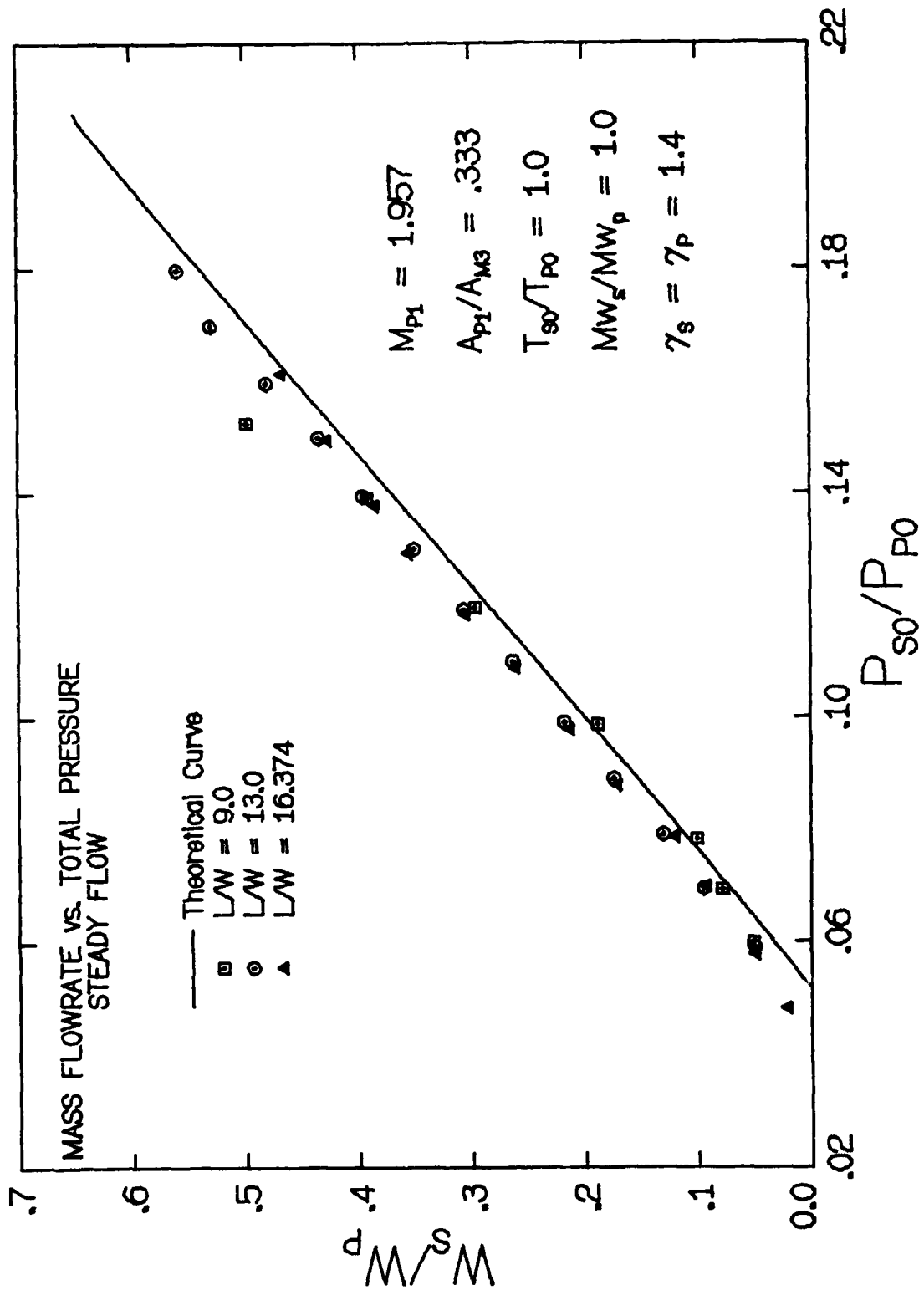


Figure 3.3.1-2 Back pressure independent steady flow values of  $w_s/w_p$  versus  $P_{S0}/P_{P0}$

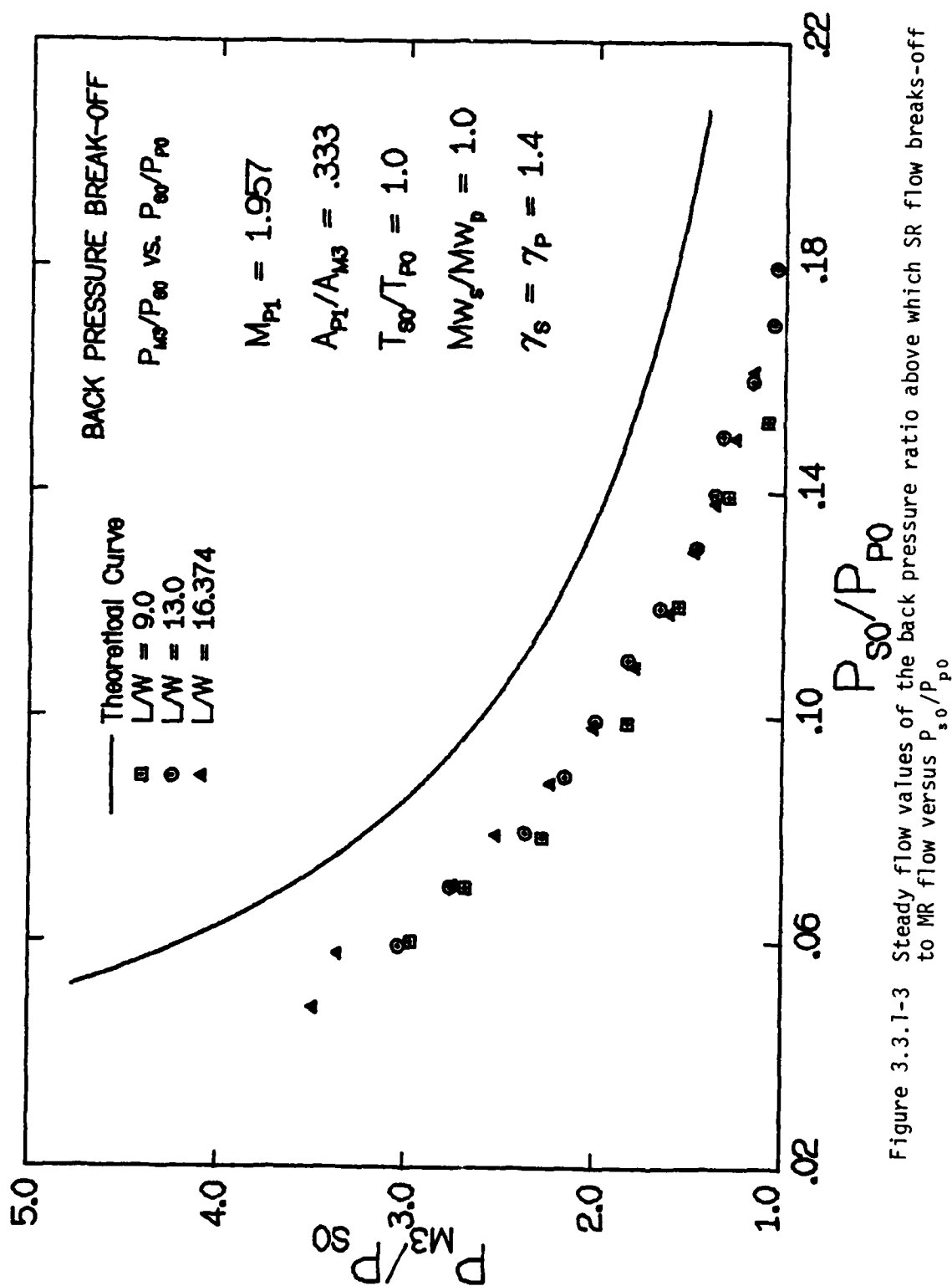


Figure 3.3.1-3 Steady flow values of the back pressure ratio above which SR flow breaks-off to MR flow versus  $P_{S0}/P_{P0}$

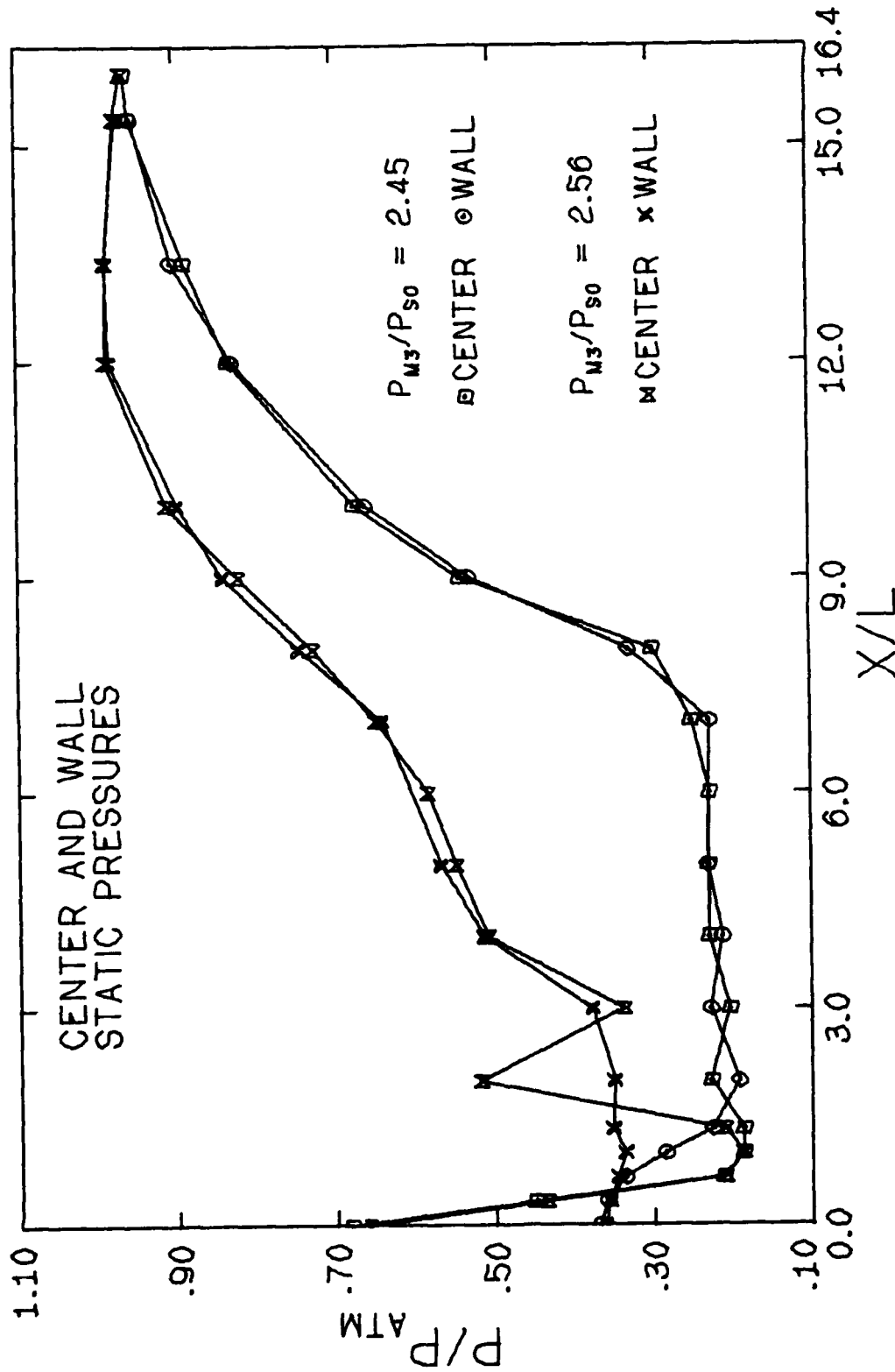


Figure 3.3.1-4 Steady flow static pressure distributions in the  $L/W = 16.374$  mixing duct at  $P_{M3}/P_{S0} = 2.45$  and  $P_{M3}/P_{S0} = 2.56$  ( $P_{S0}/P_{P0} \approx .078$ )

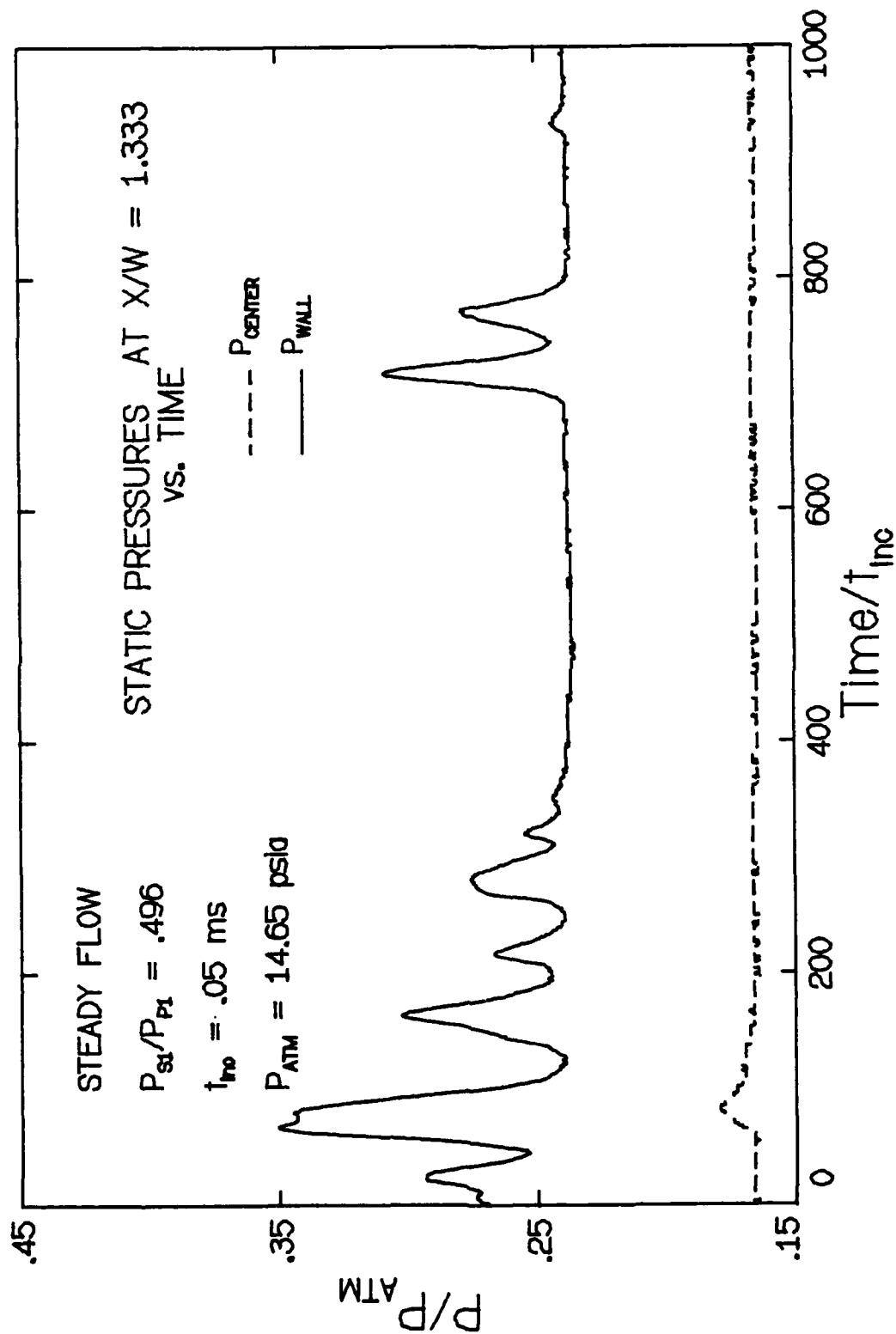


Figure 3.3.2-1 Large amplitude pulses were observed in the subsonic wall flow of both steady and periodic driver experiments ( $P_{s0}/P_{p0} \approx .070$ )

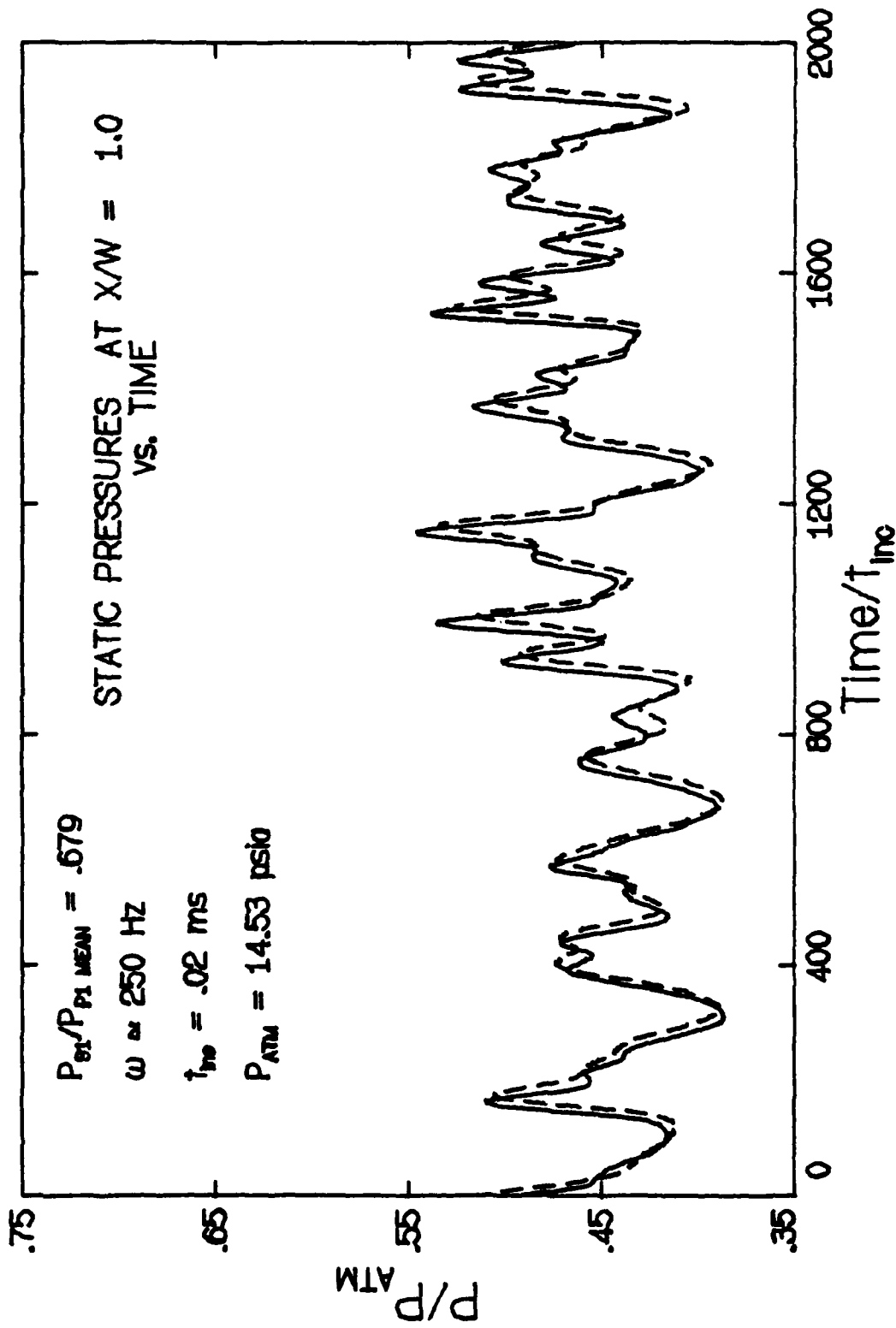


Figure 3.3.2-2 Wall flow static pressures were found to be symmetric about the primary flow centerline ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

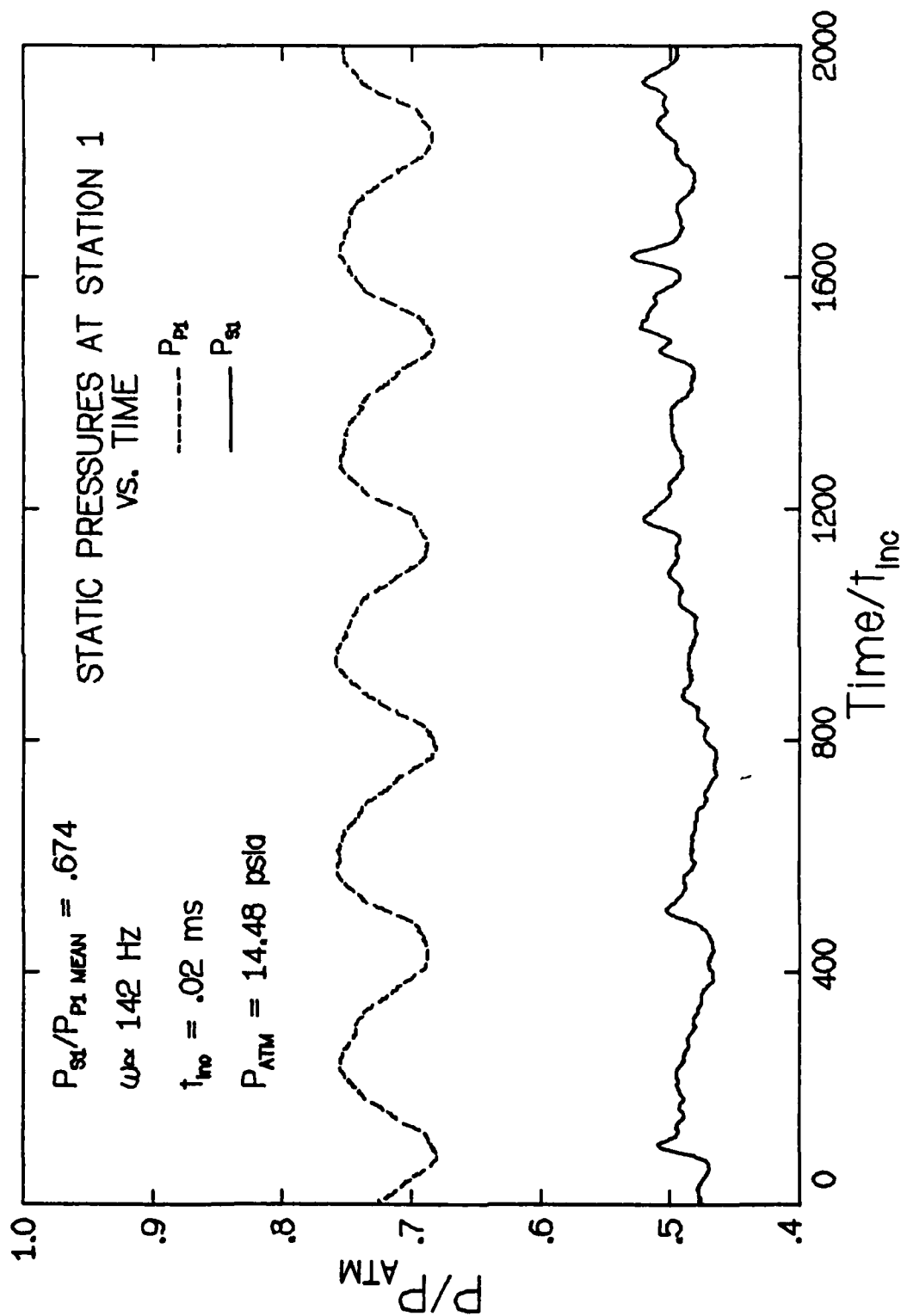


Figure 3.3.2-3 Primary and secondary static pressures at Station 1 for the 142 Hz driver ejector flow versus time ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

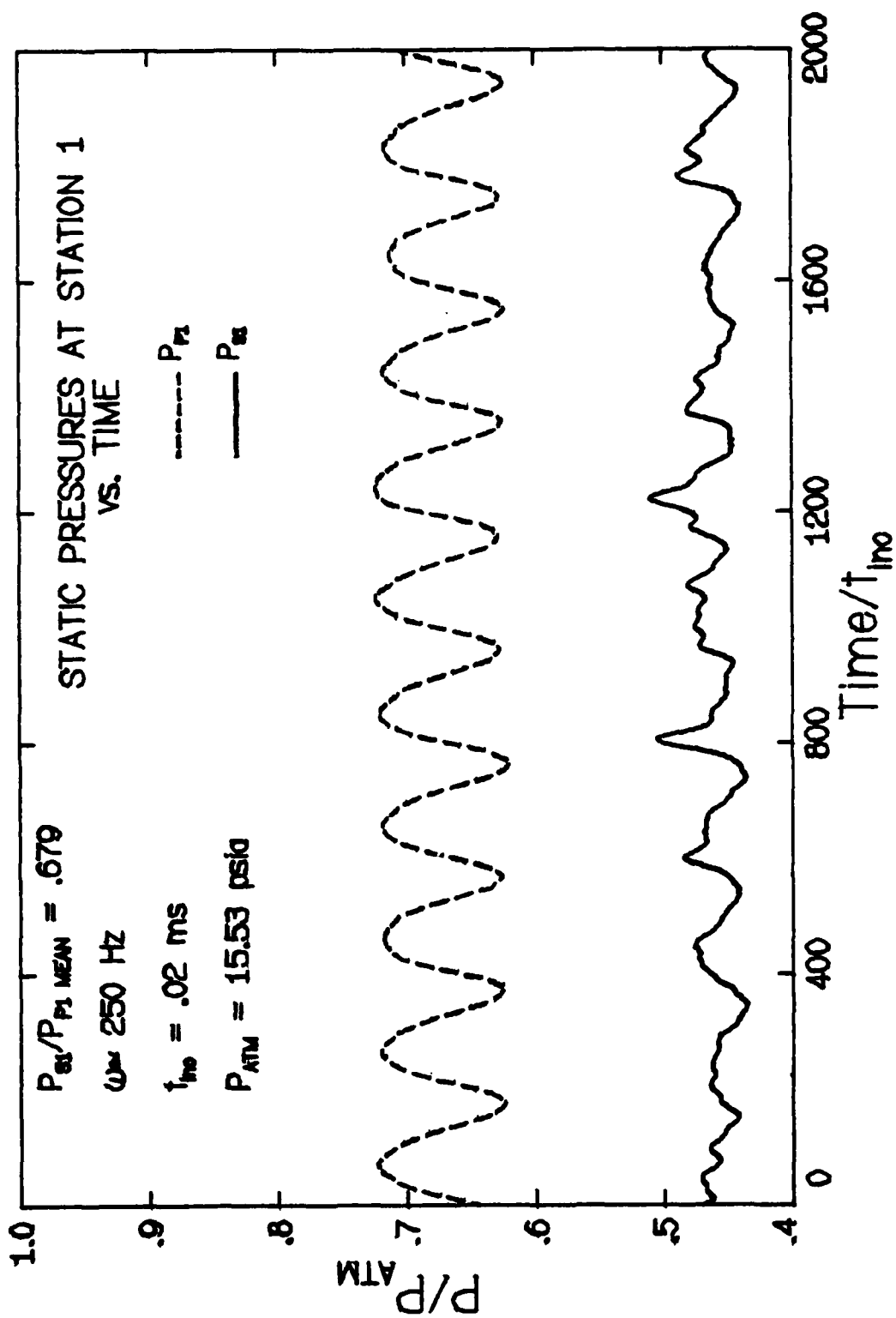


Figure 3.3.2-4 Primary and secondary static pressures at Station 1 for the 250 Hz driver ejector flow versus time ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

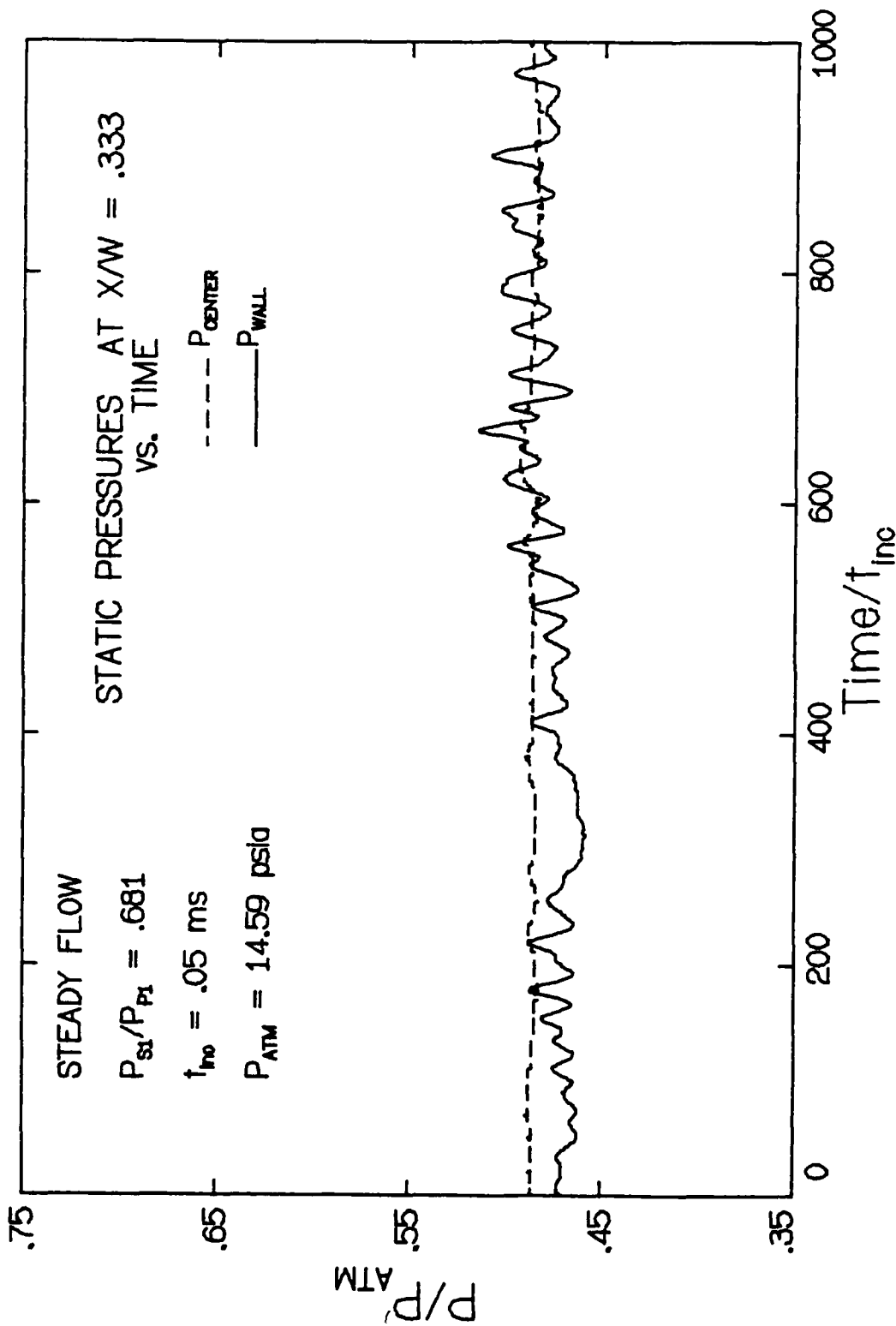


Figure 3.3.2-5 Small disturbances in the subsonic wall flow of the steady driver ejector flow ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

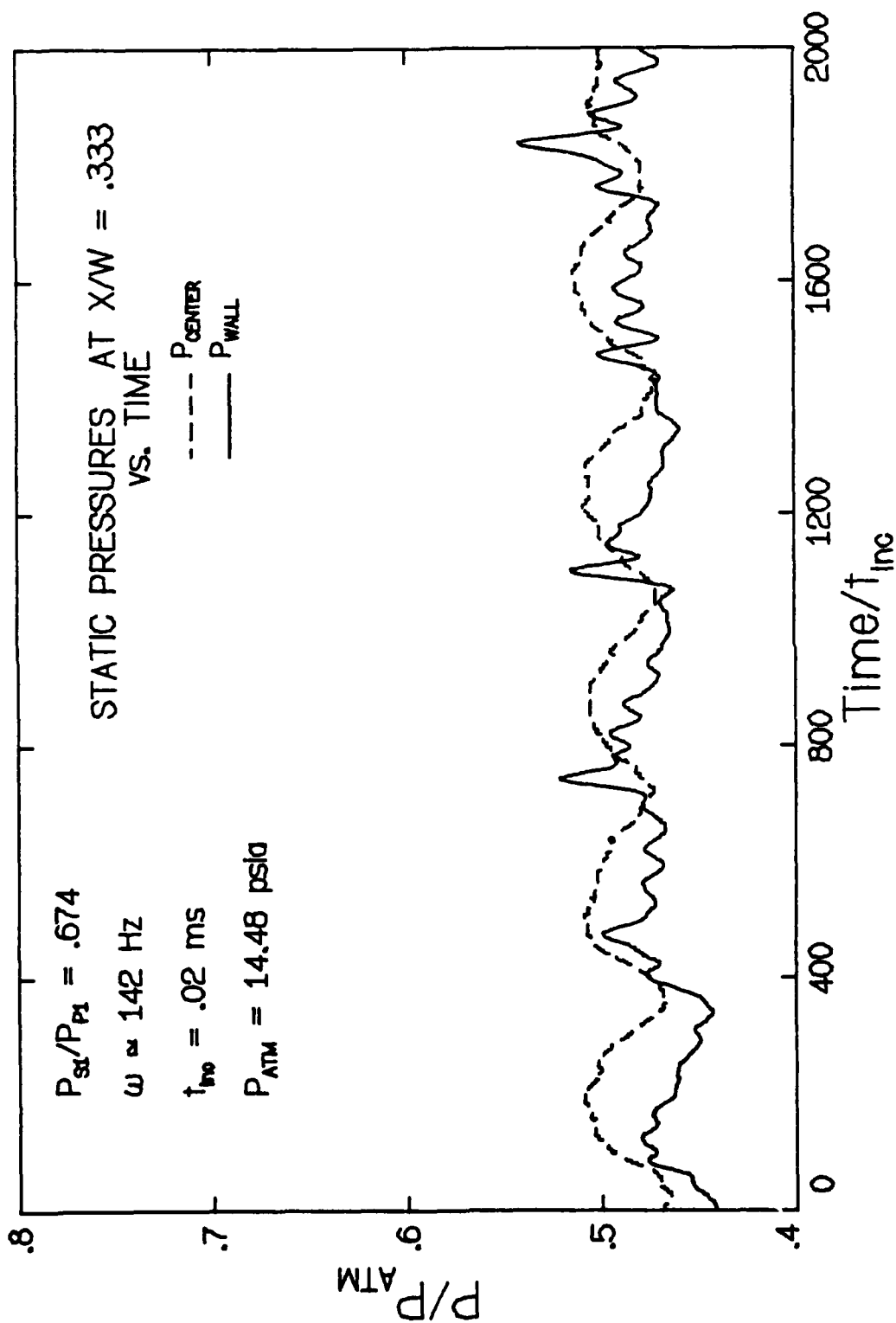


Figure 3.3.2-6 Static pressures versus time in the 142 Hz driver ejector flow  
 at  $X/W = .333$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

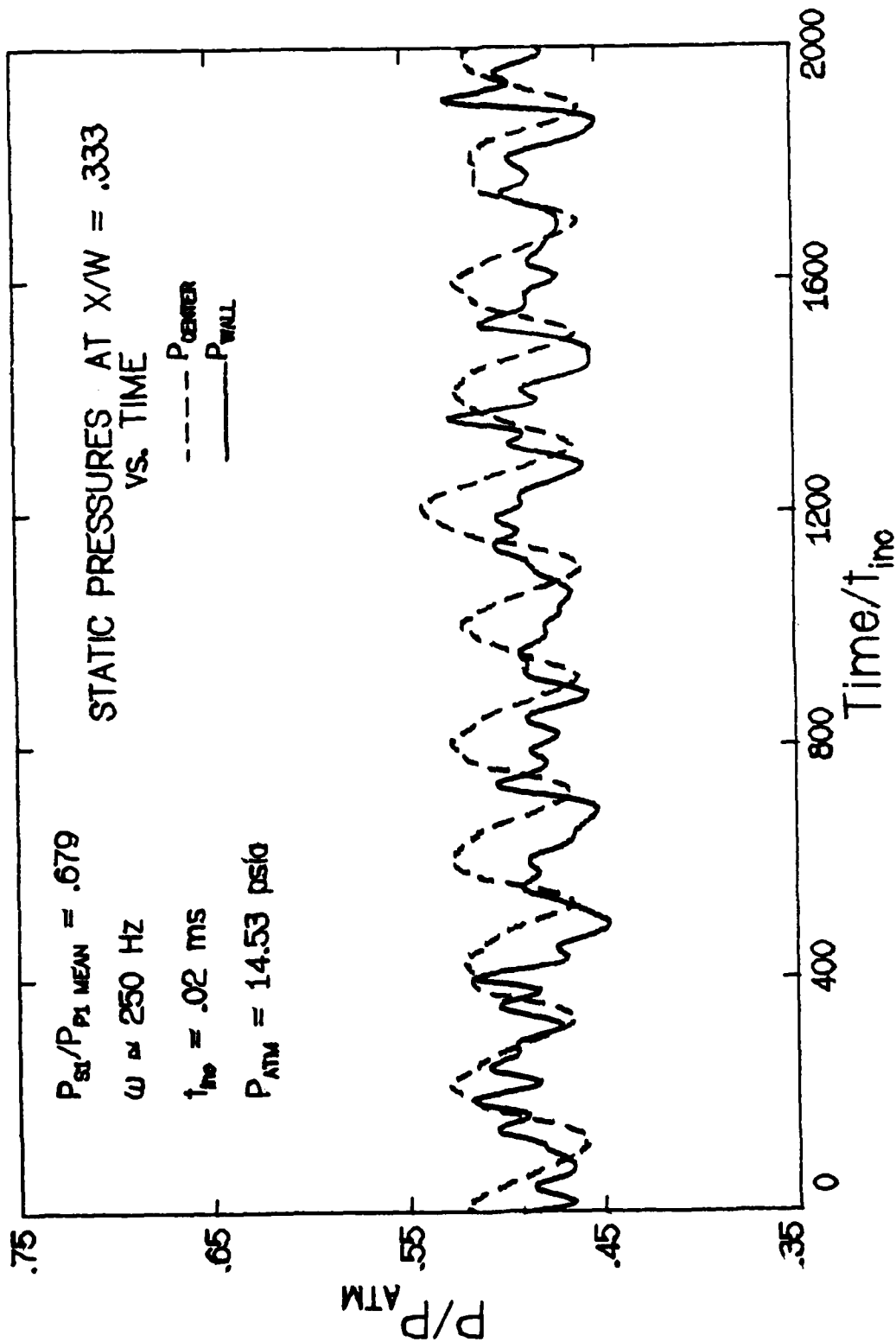


Figure 3.3.2-7 Static pressures versus time in the 250 Hz driver ejector flow  
 at  $X/W = .333$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

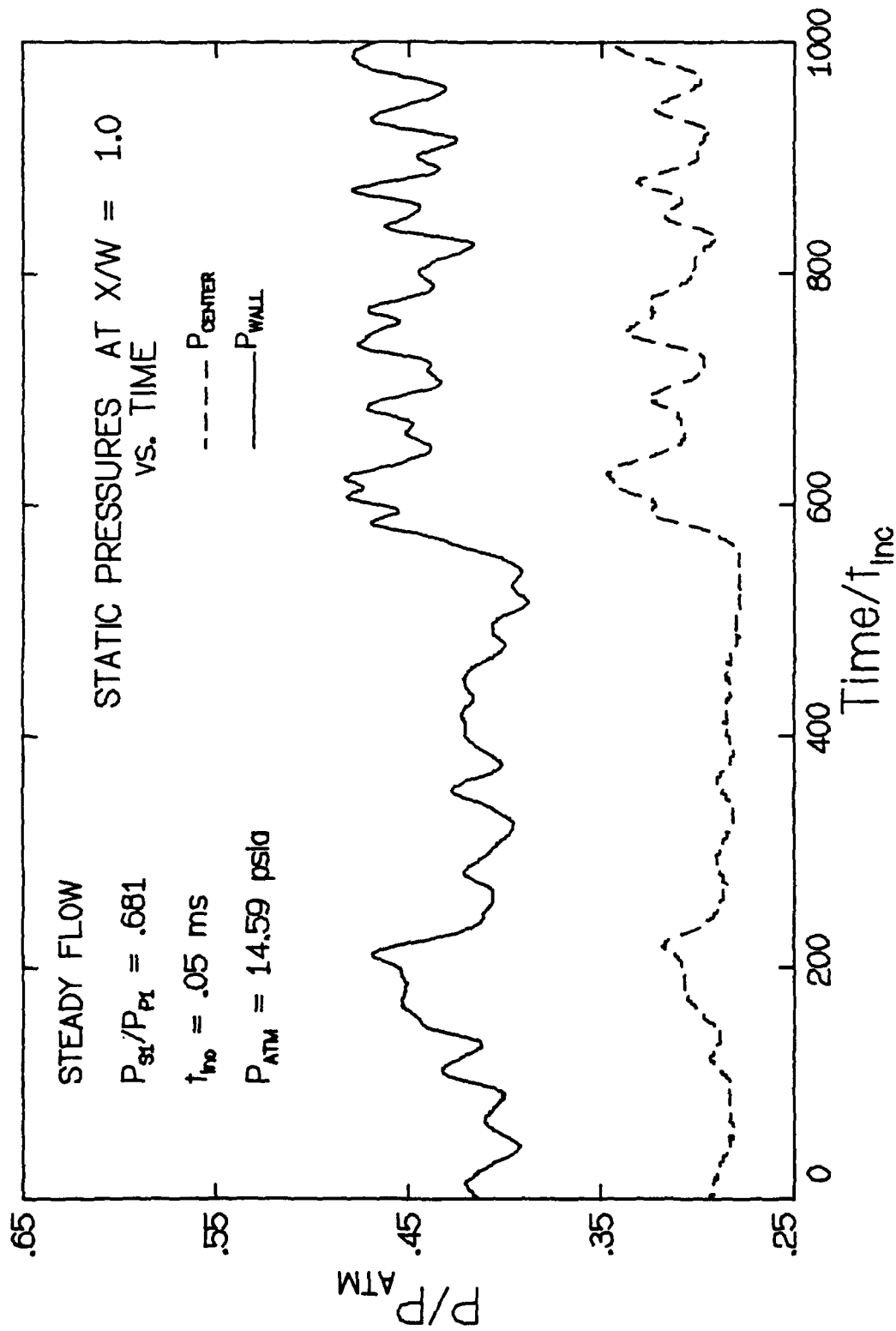


Figure 3.3.2-8 Static pressures versus time in the steady driver ejector flow at  $X/W = 1.00$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

AD-A084 786

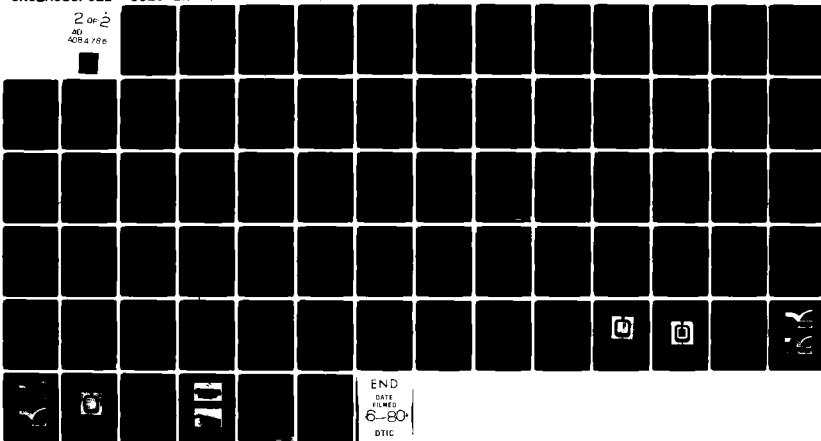
ILLINOIS UNIV AT URBANA-CHAMPAIGN DEPT OF MECHANICAL --ETC F/6 20/4  
AN EXPERIMENTAL AND THEORETICAL INVESTIGATION OF MULTIPLE DUCTE--ETC(U)  
JAN 80 H L PETRIE, A L ADDY DAA629-76-6-0200  
UILU-ENG-80-4002

UNCLASSIFIED

ARO-13737.2-EX

ML

2 of 2  
AD  
A084 786



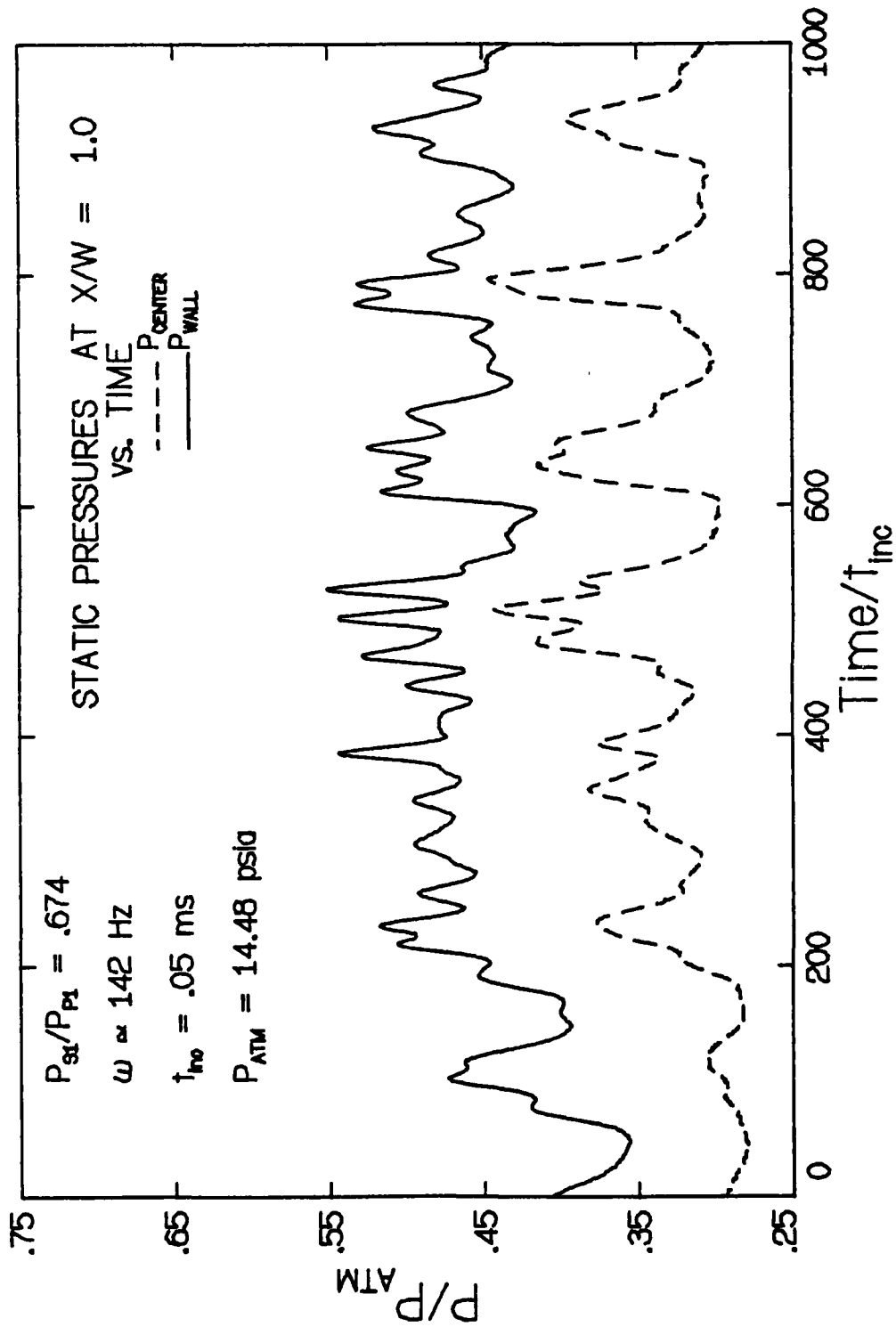


Figure 3.3.2-9 Static pressures versus time in the 142 Hz driver ejector flow at  $X/W = 1.00$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

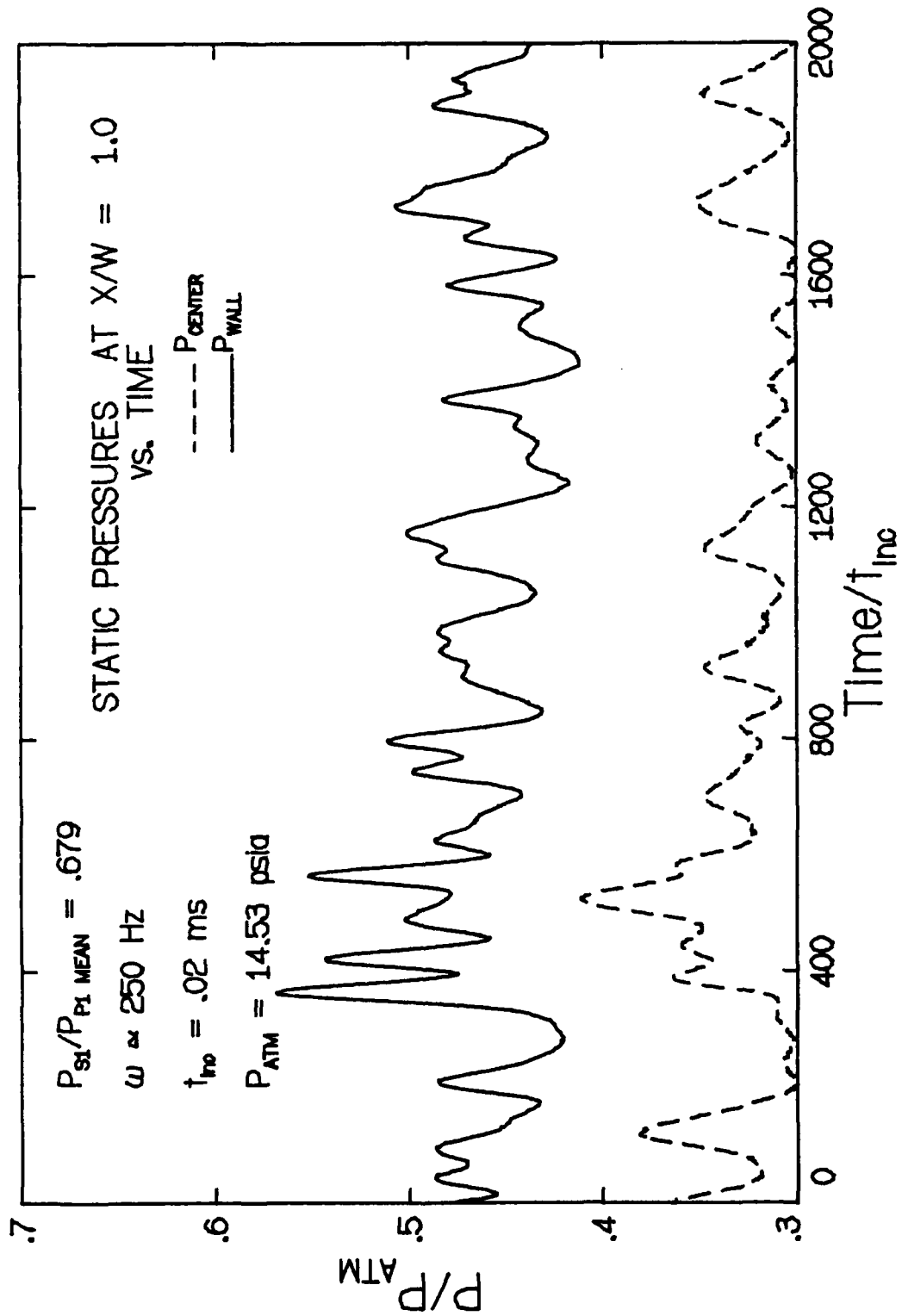


Figure 3.3.2-10 Static pressures versus time in the 250 Hz driver ejector flow at  $X/W = 1.00$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

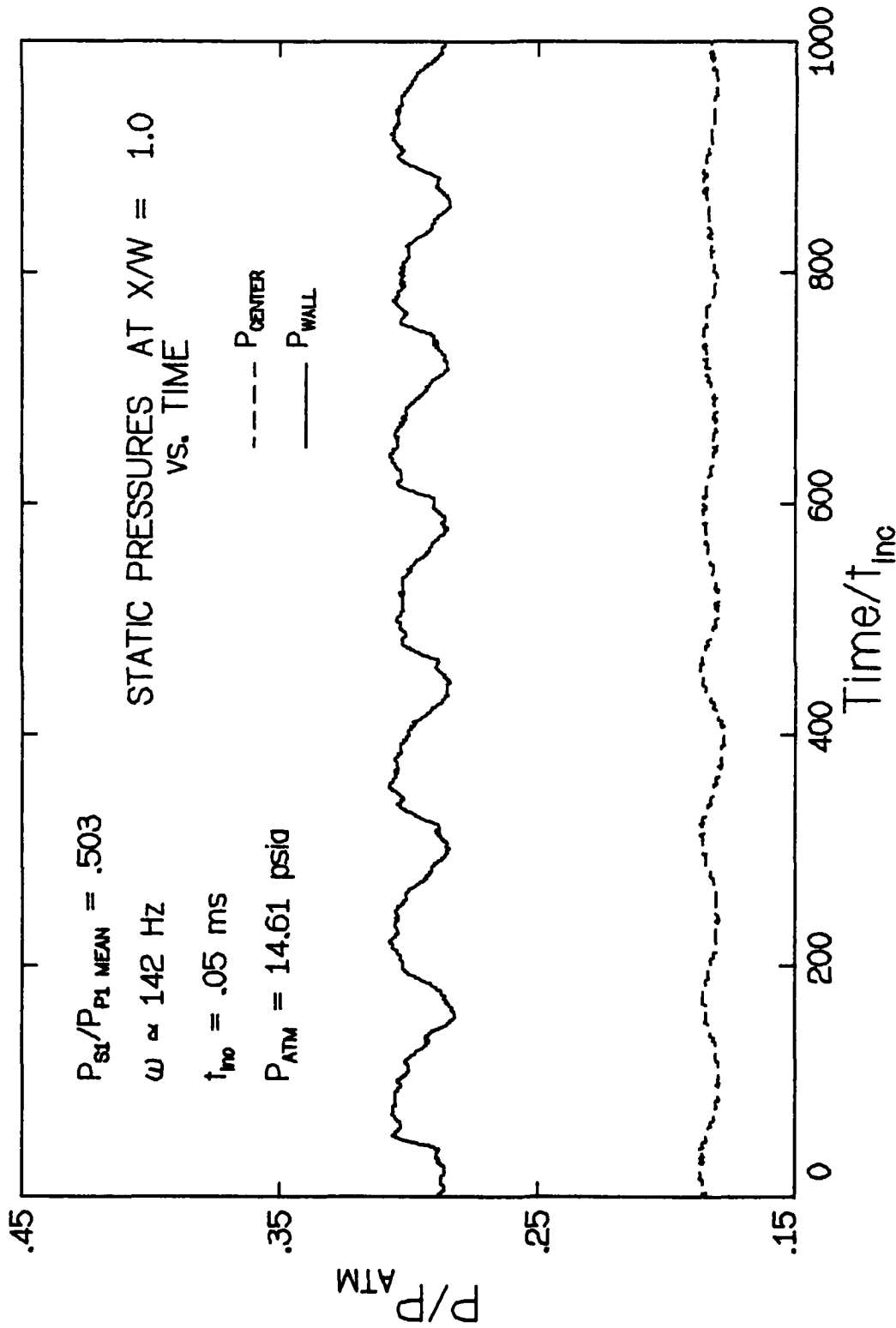


Figure 3.3.2-11 Static pressure pulses in a highly expanded shock free flow.  $P_{\text{ms}}/P_{s0}$  is relatively low ( $L/W = 13.0$ ,  $P_{s0}/P_{p0} \approx .070$ )

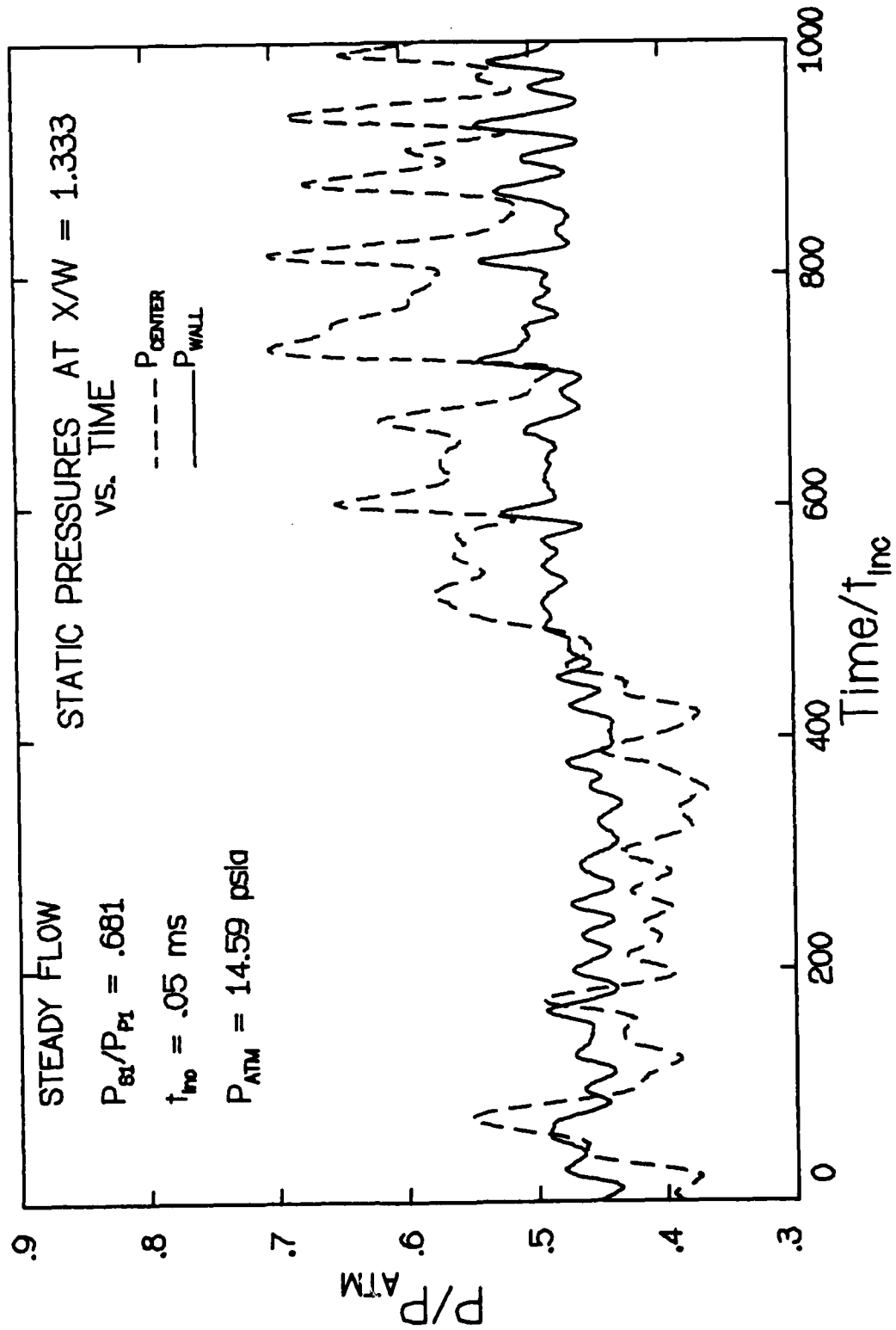


Figure 3.3.2-12 Static pressures versus time in the steady driver ejector flow  
at  $X/W = 1.333$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

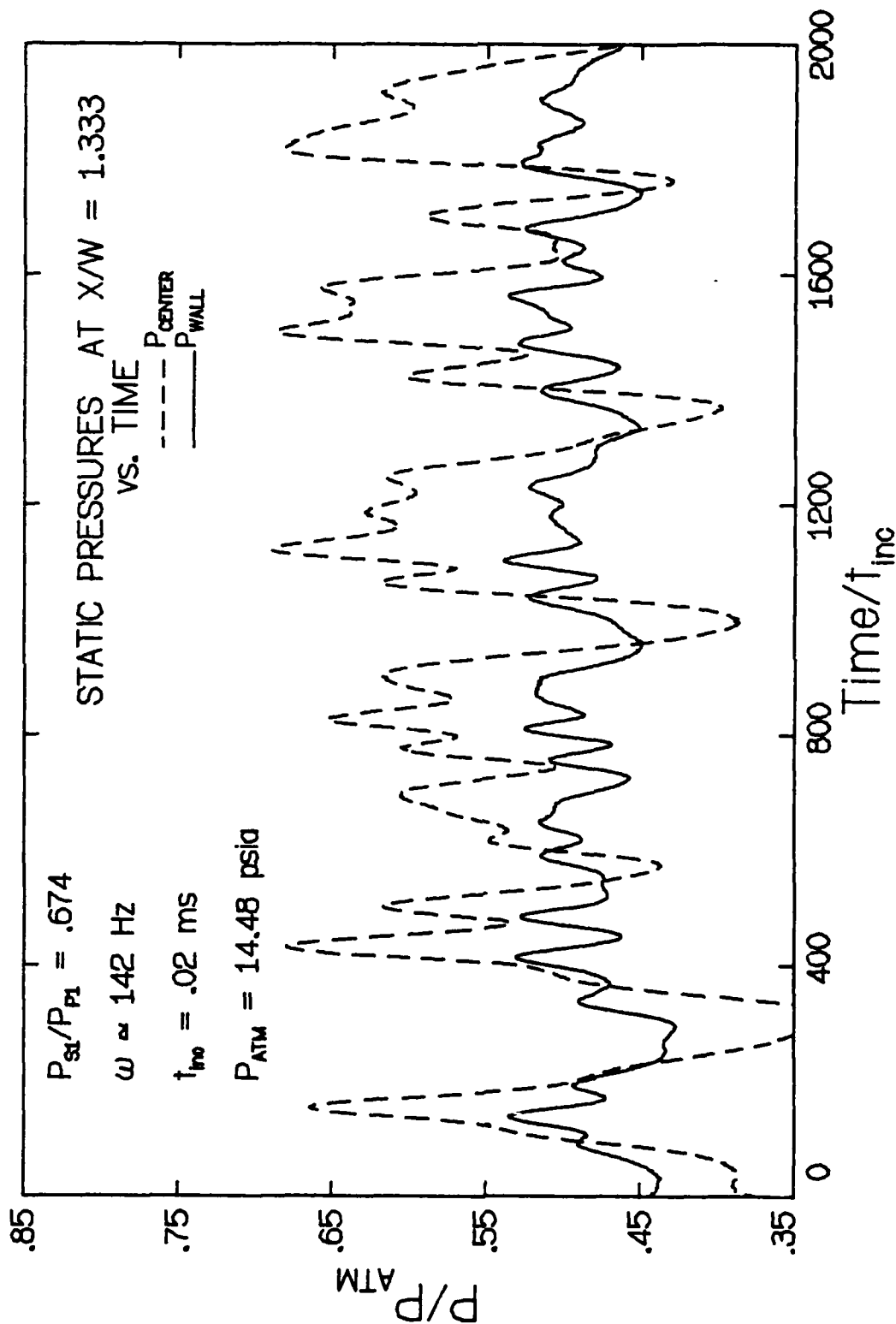


Figure 3.3.2-13 Static pressures versus time in the 142 Hz driver ejector flow  
at  $X/W = 1.333$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

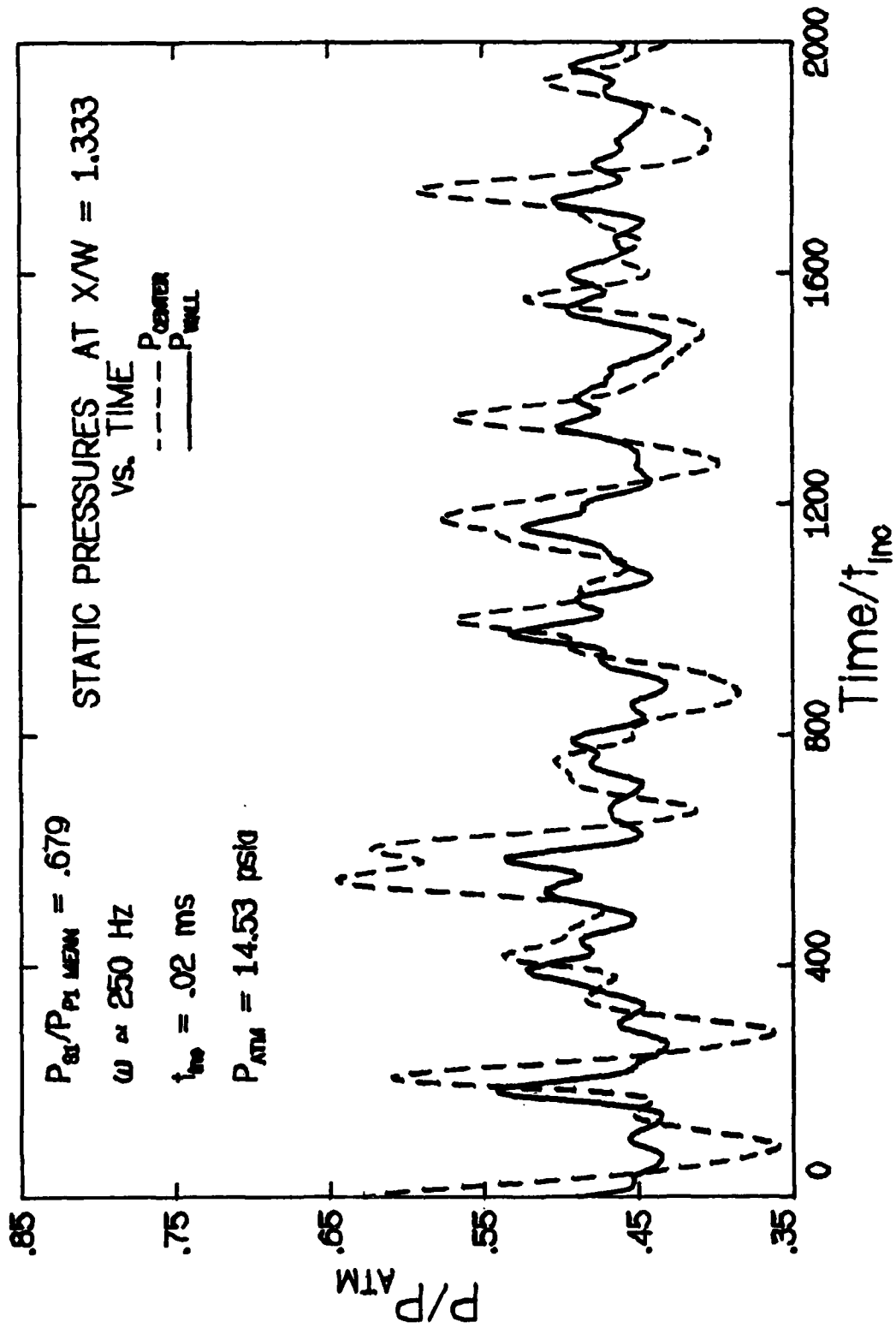


Figure 3.3.2-14 Static pressures versus time in the 250 Hz driver ejector flow at  $X/W = 1.333$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

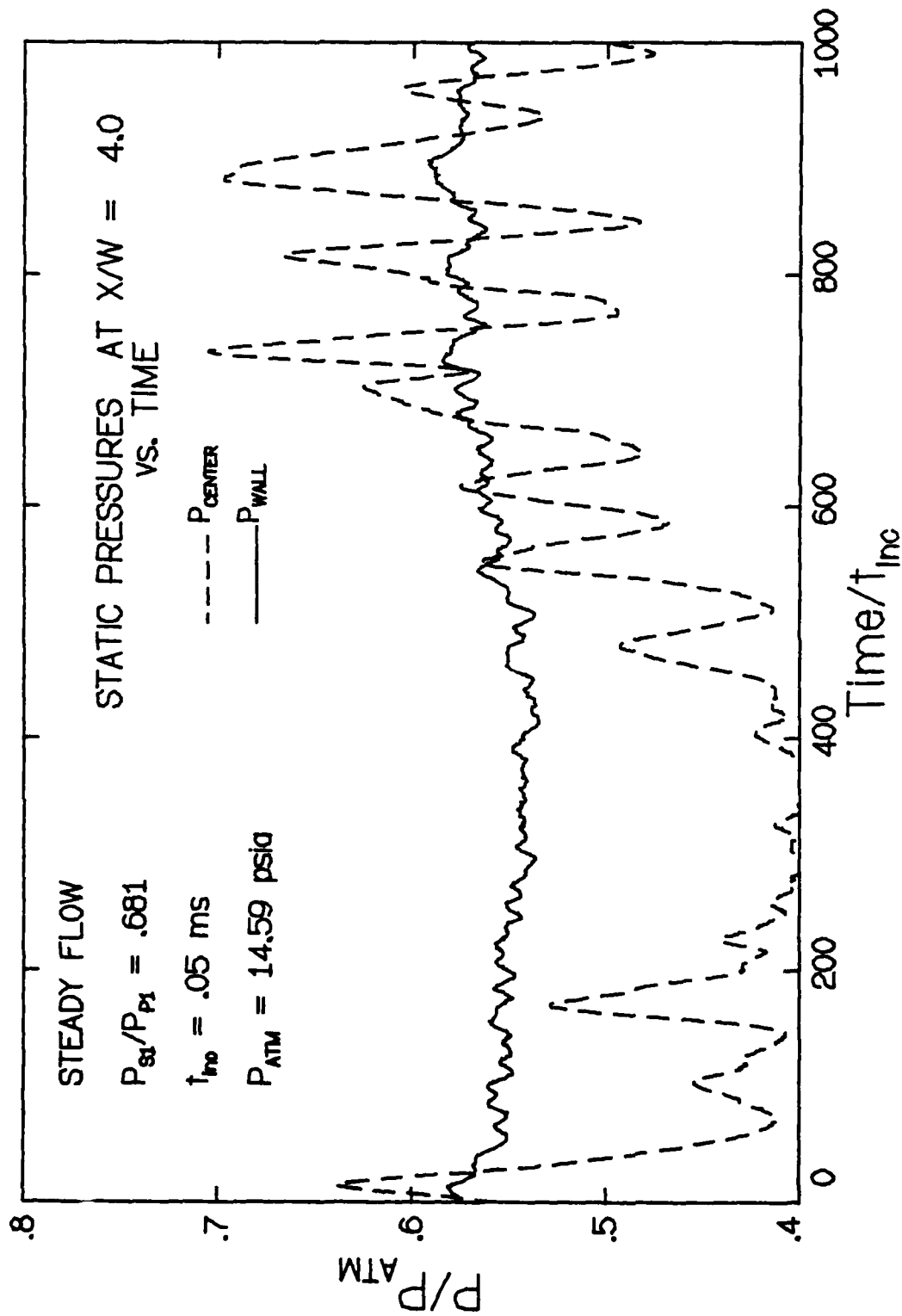


Figure 3.3.2-15 Static pressures versus time in the steady driver ejector flow  
at  $X/W = 4.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

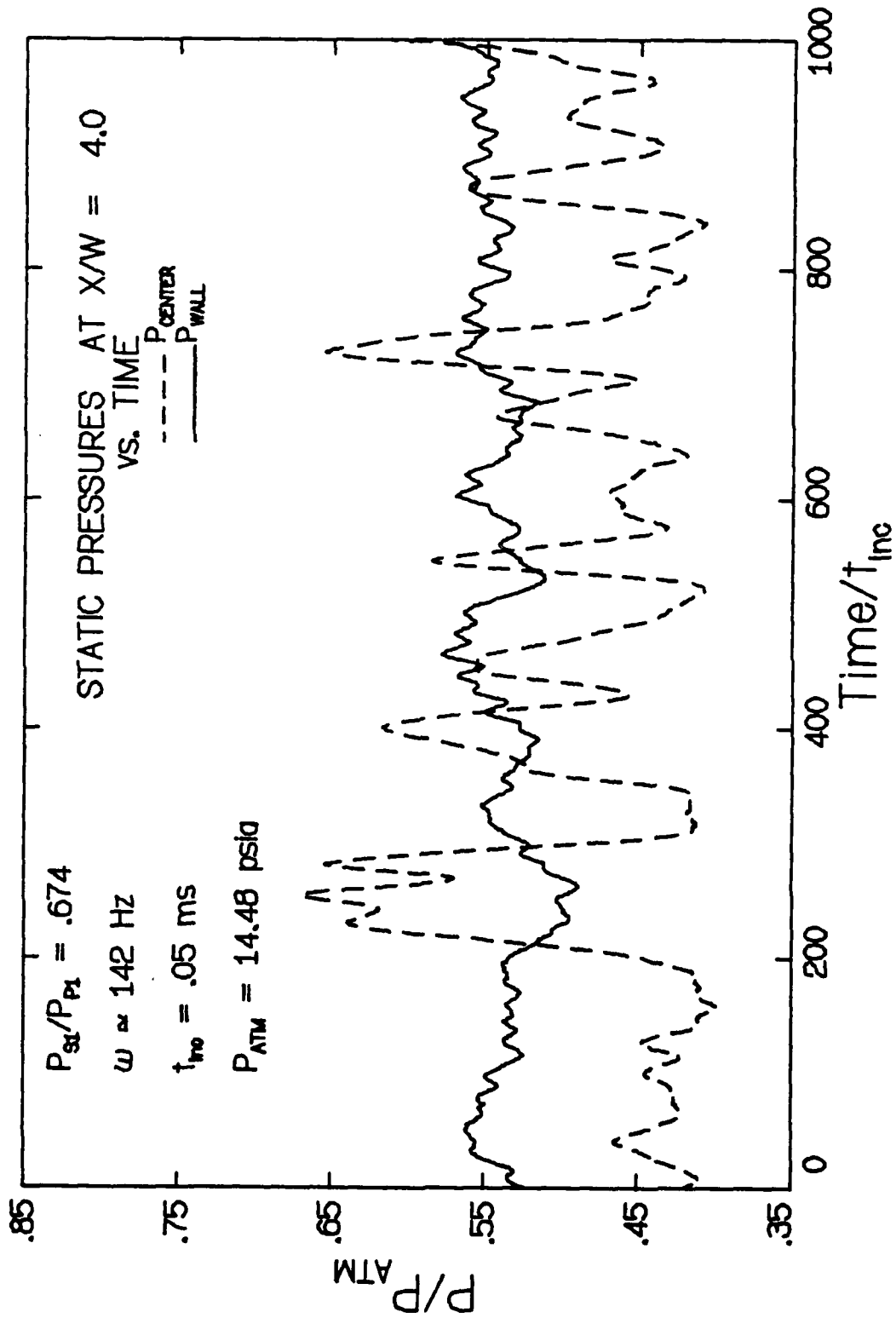


Figure 3.3.2-16 Static pressures versus time in the 142 Hz driver ejector flow at  $X/W = 4.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

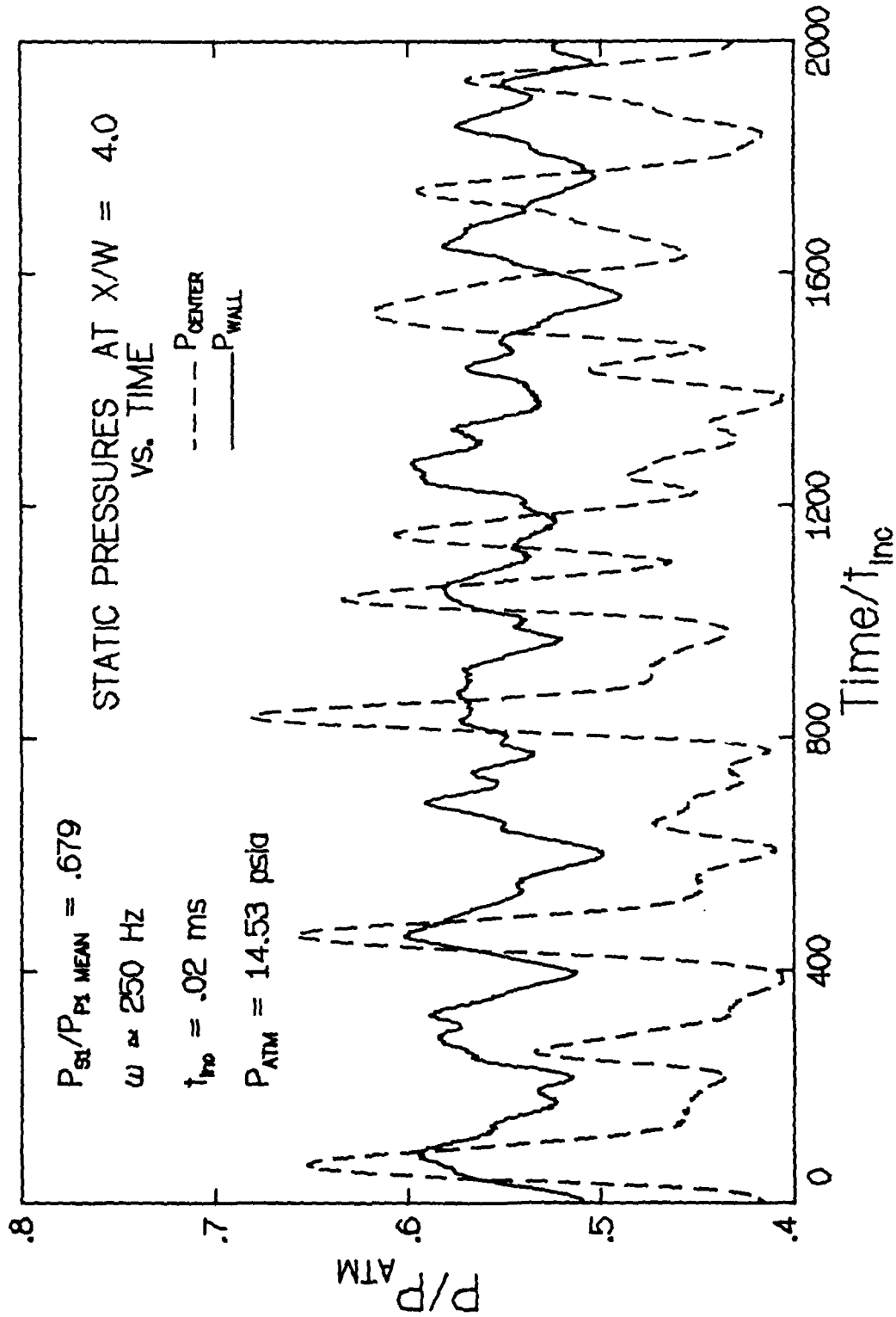


Figure 3.3.2-17 Static pressures versus time in the 250 Hz driver ejector flow  
 at  $X/W = 4.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} = .100$ )

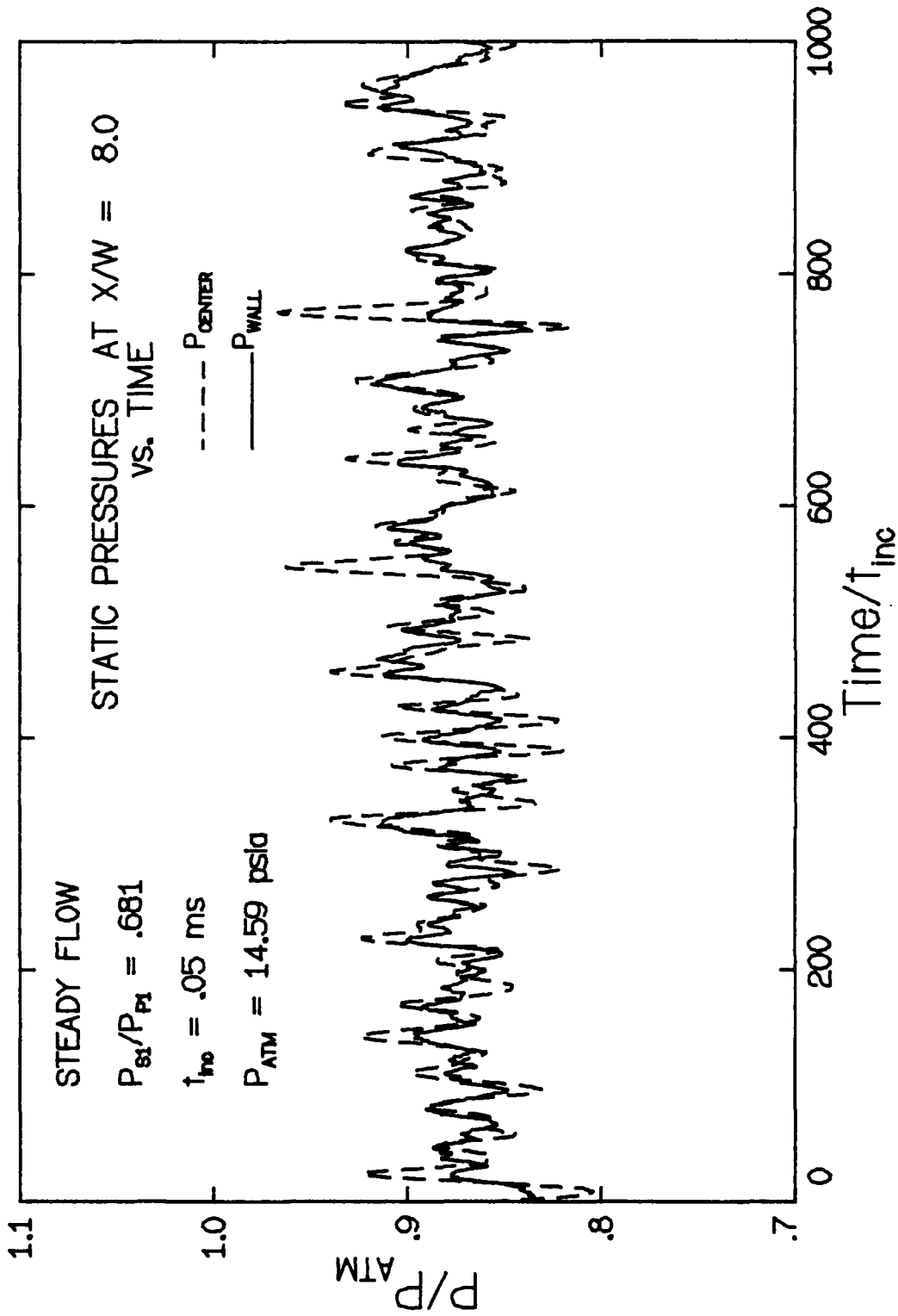


Figure 3.3.2-18 Static pressures versus time in the steady driver ejector flow  
at  $X/W = 8.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

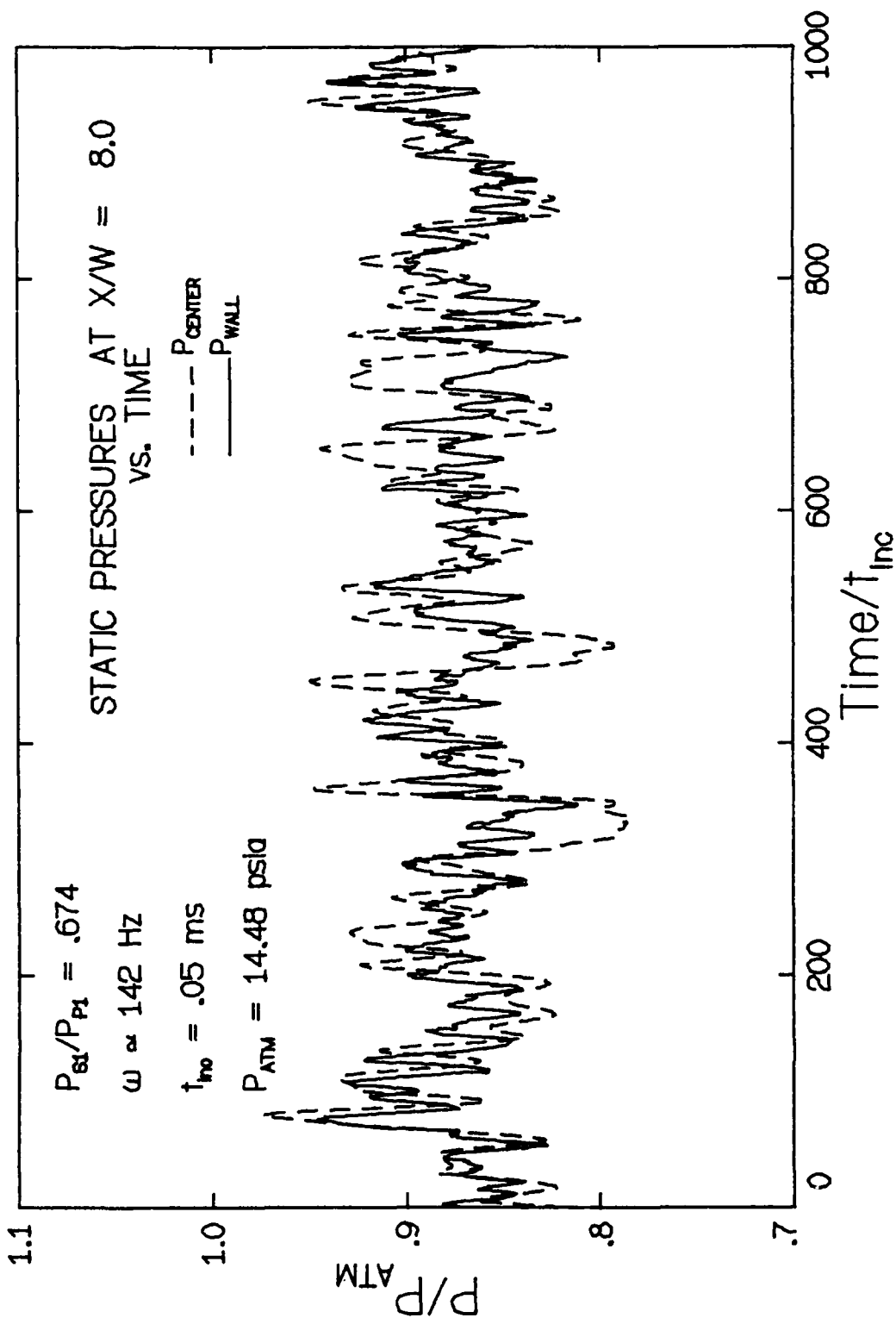


Figure 3.3.2-19 Static pressures versus time in the 142 Hz driver ejector flow at  $X/W = 8.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

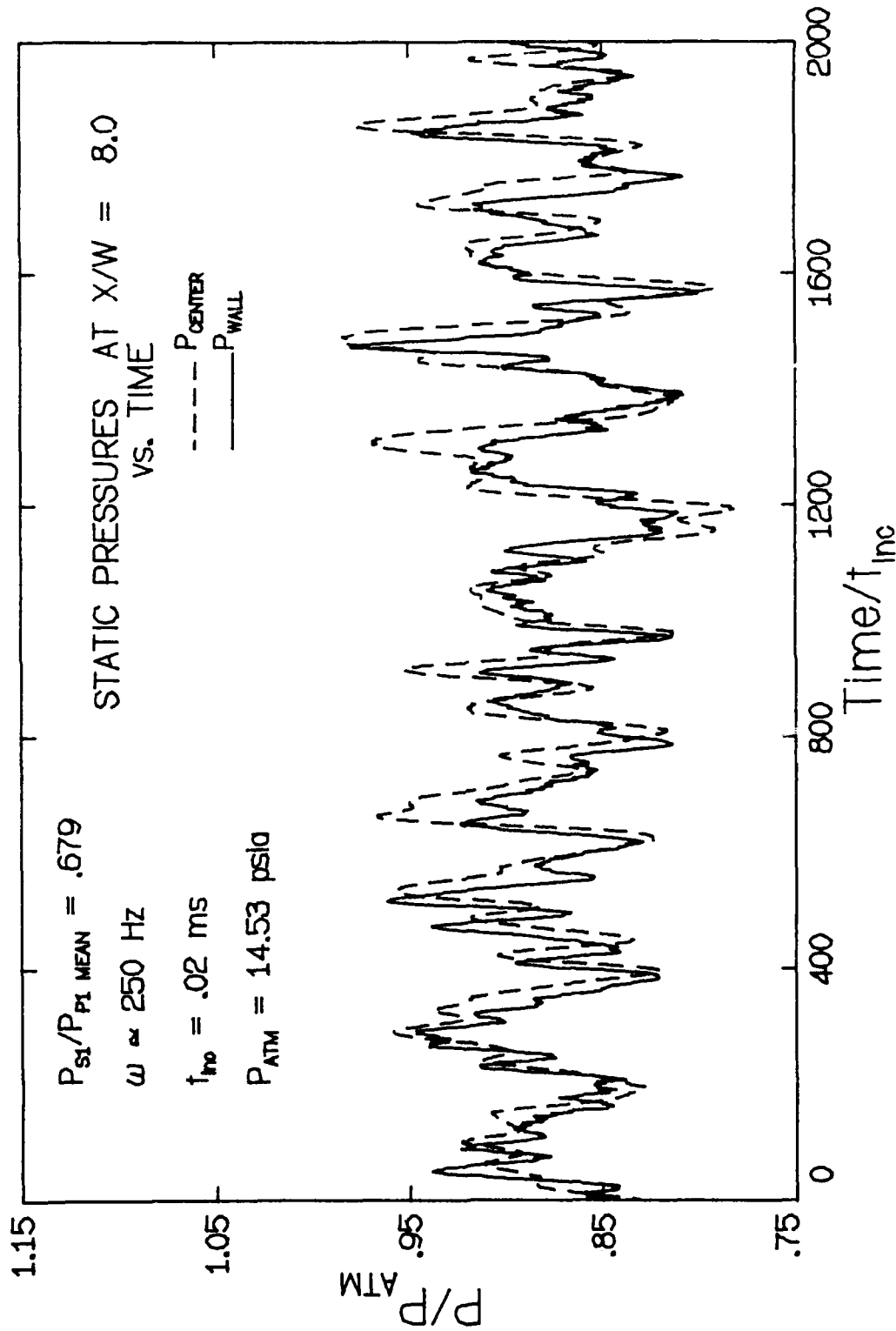


Figure 3.3.2-20 Static pressures versus time in the 250 Hz driver ejector flow  
 at  $X/W = 8.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

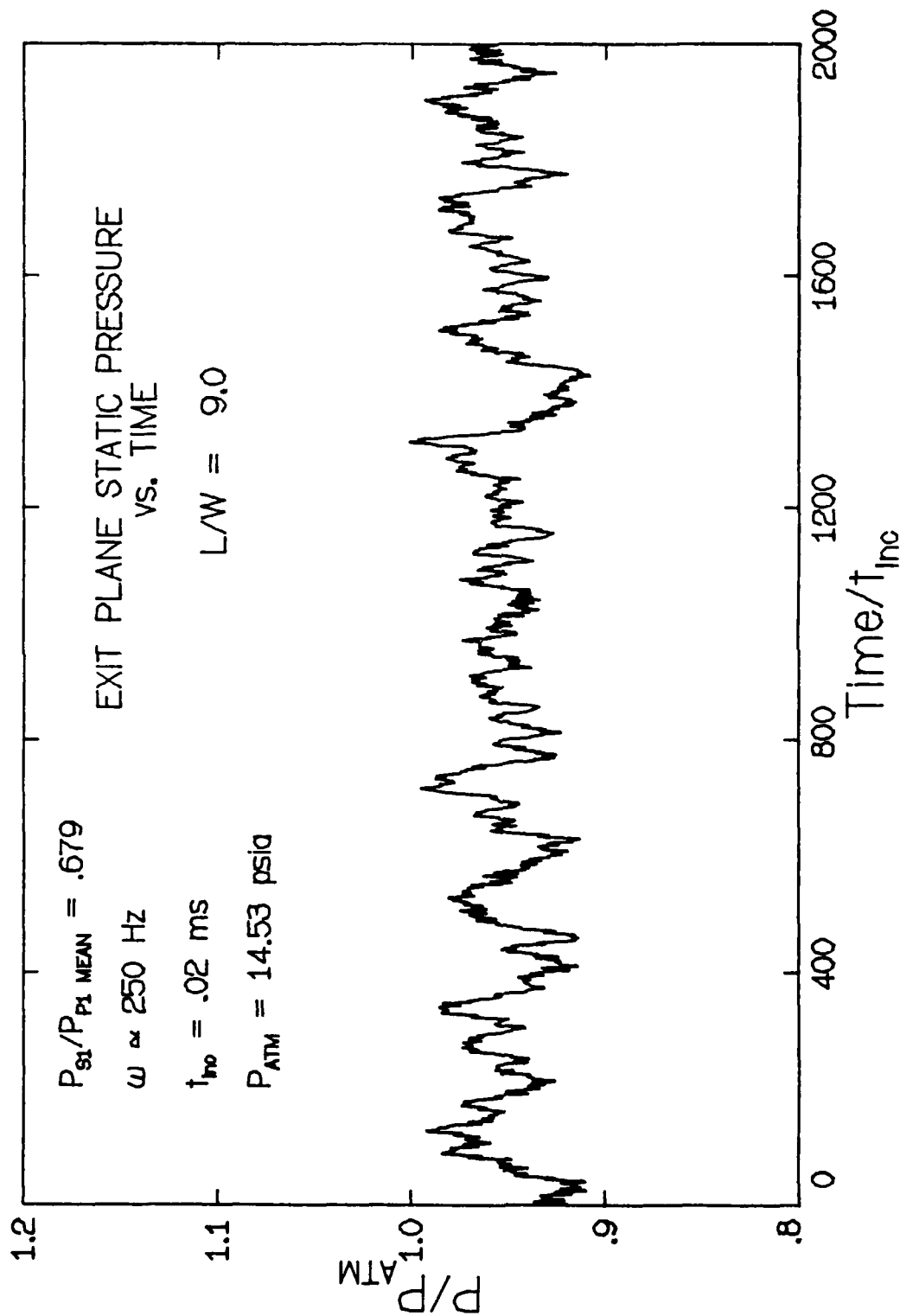


Figure 3.3.2-21 The exit plane static pressure versus time on the primary flow centerline ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

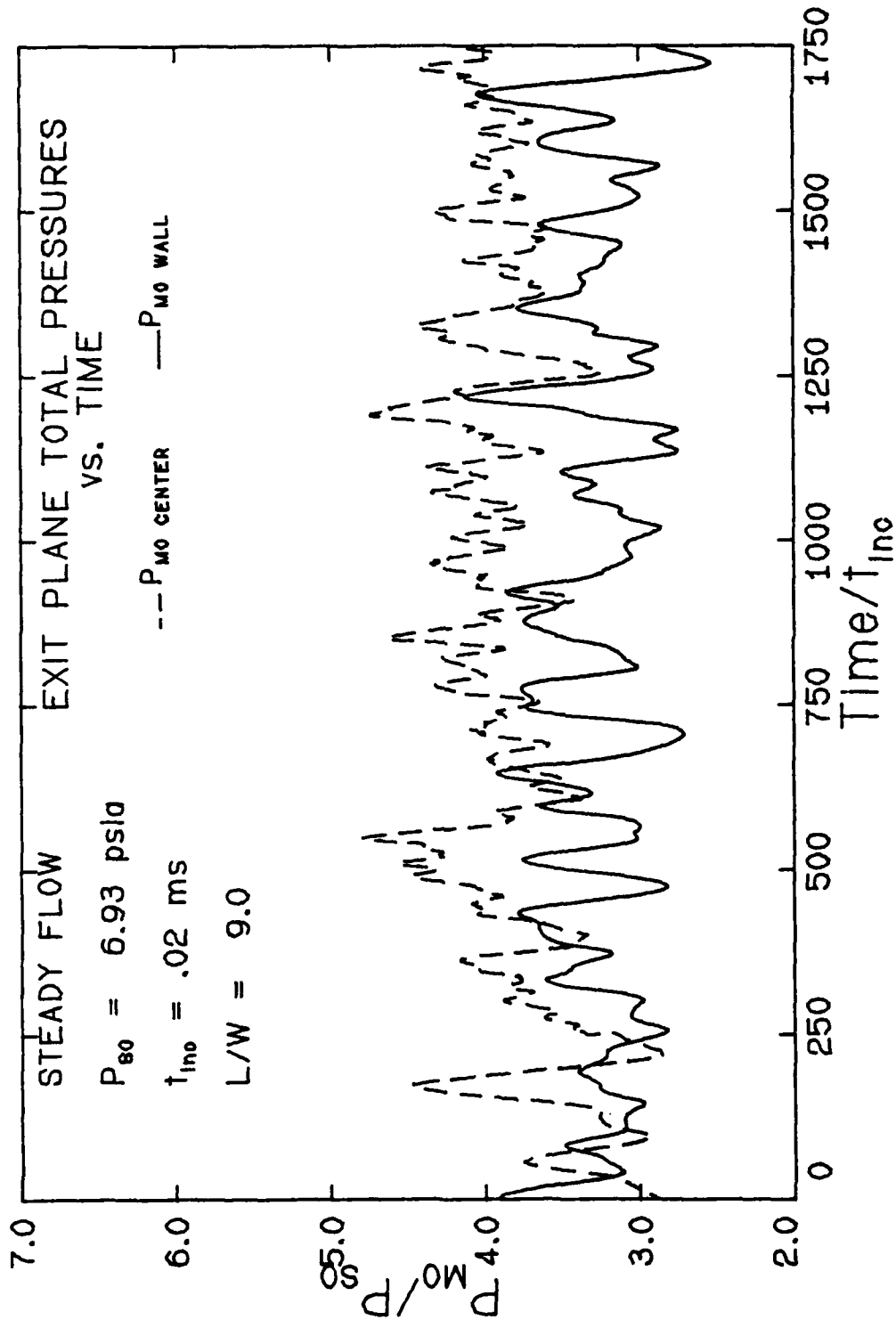


Figure 3.3.2-22 Exit plane stagnation pressures versus time in the steady driver ejector flow ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

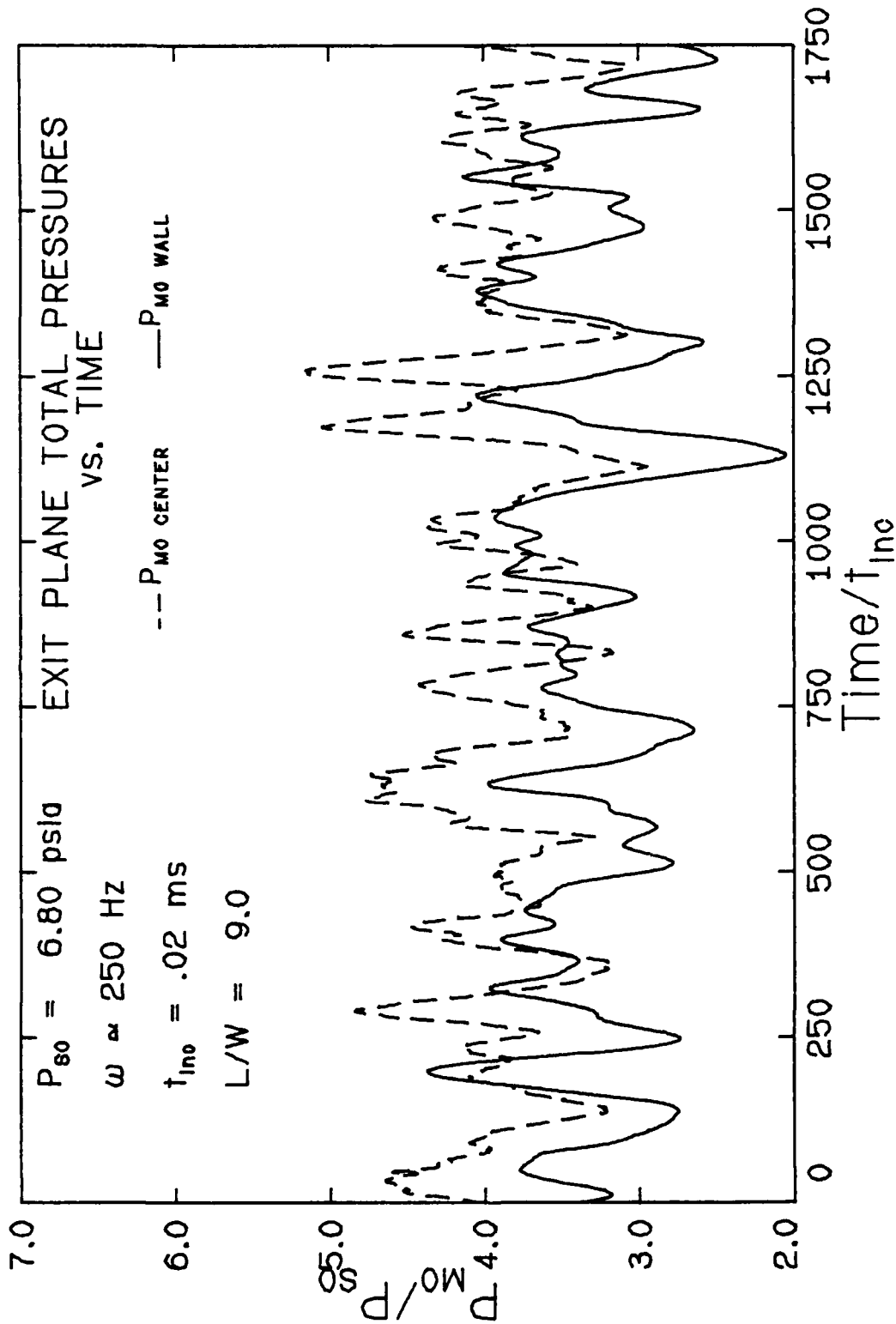


Figure 3.3.2-23 Exit plane stagnation pressures versus time in the 250 Hz driver  
 ejector flow ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .100$ )

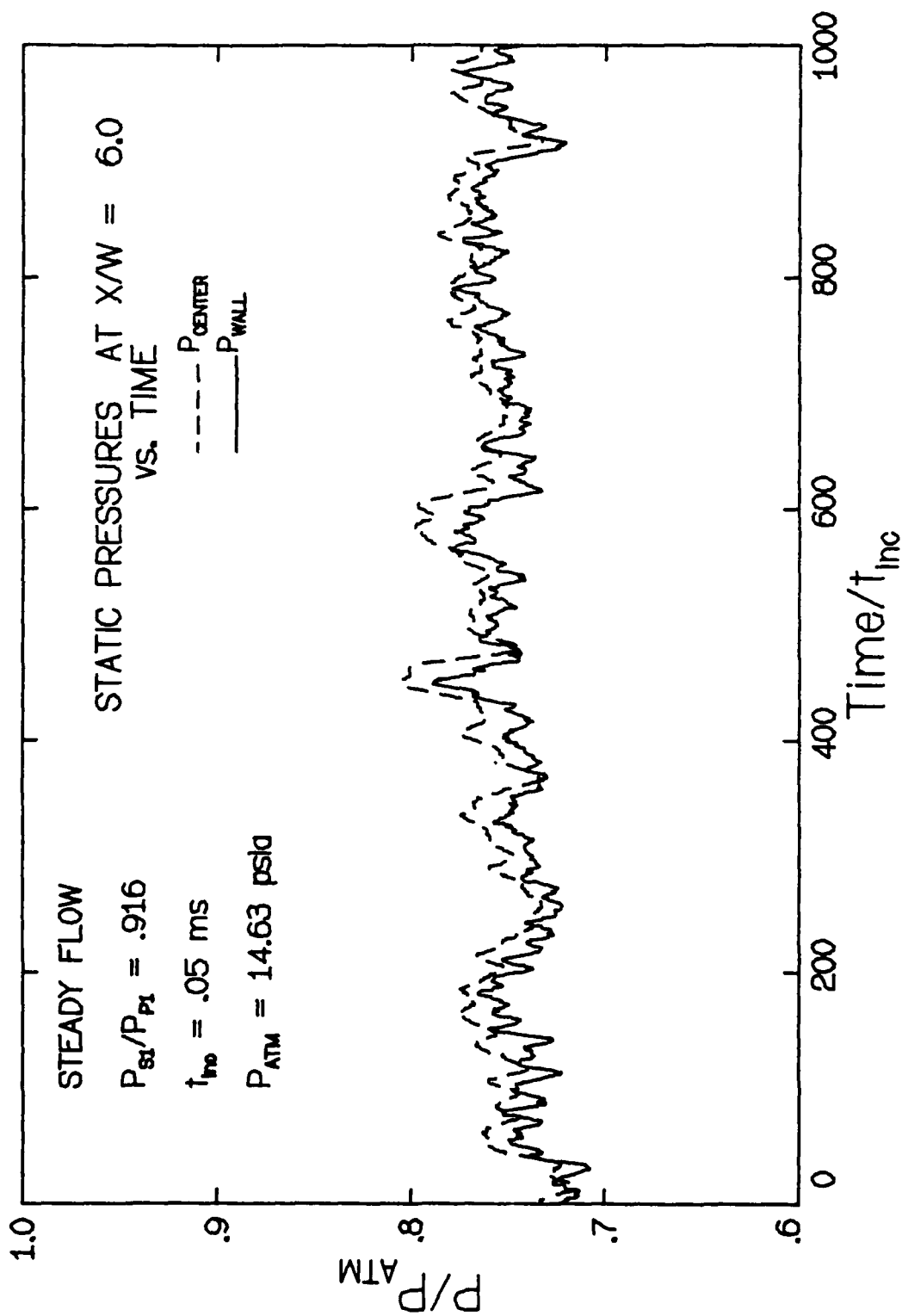


Figure 3.3.2-24 Static pressures versus time in the steady driver ejector flow at  $X/W = 6.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .160$ )

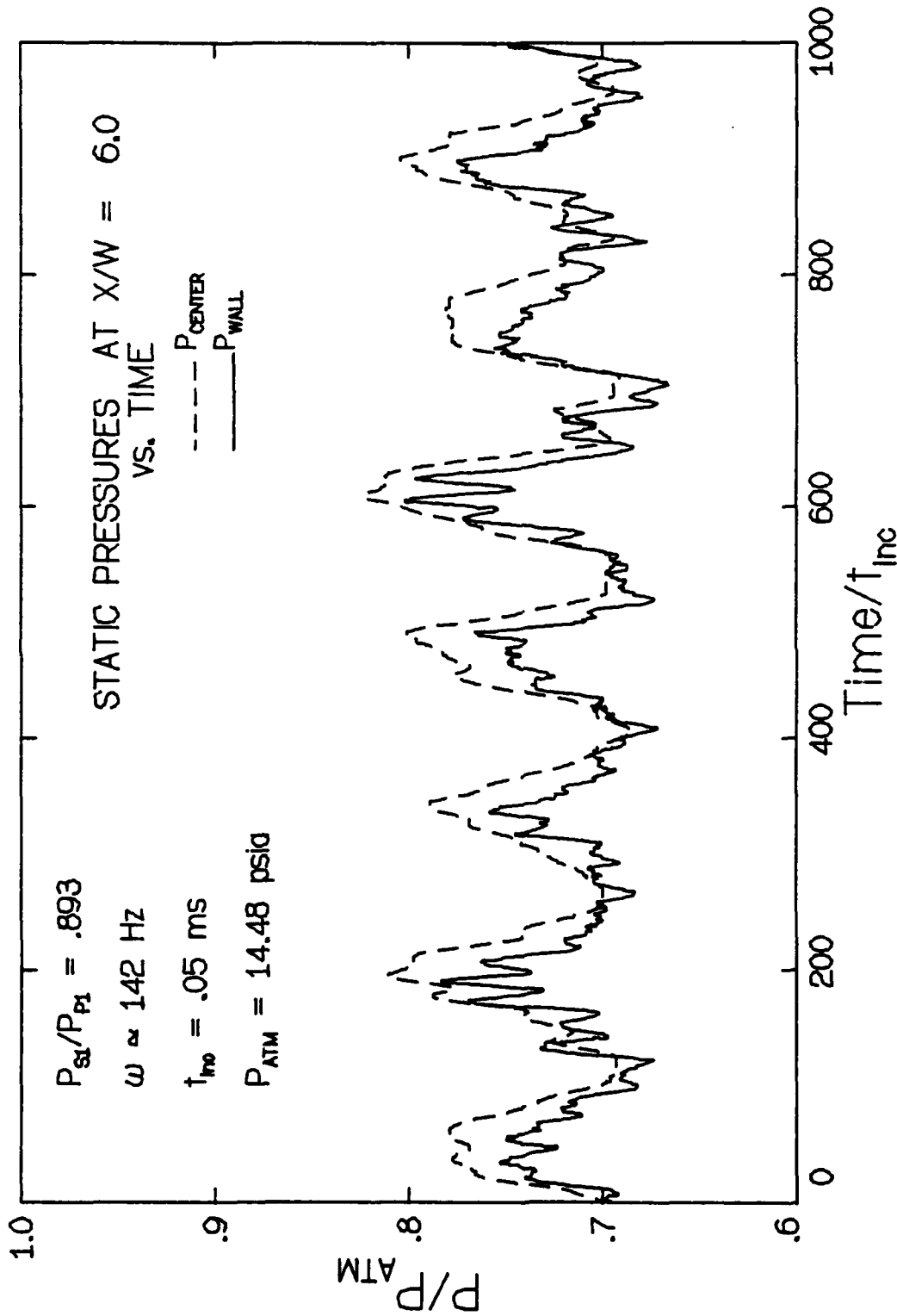


Figure 3.3.2-25 Static pressures versus time in the 142 Hz driver ejector flow  
 at  $X/W = 6.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .160$ )

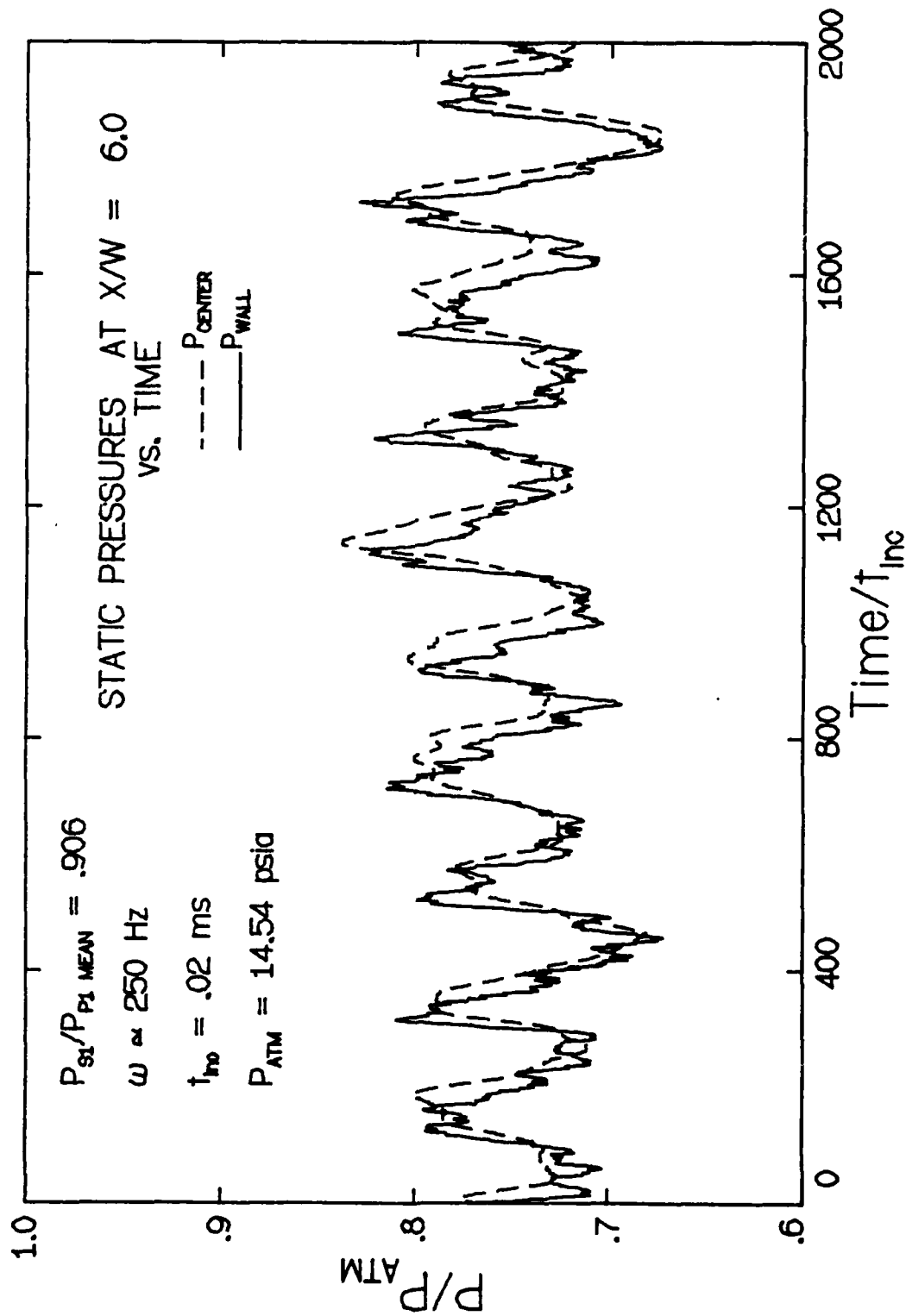


Figure 3.3.2-26 Static pressures versus time in the 250 Hz driver ejector flow  
 at  $X/W = 6.0$  ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .160$ )

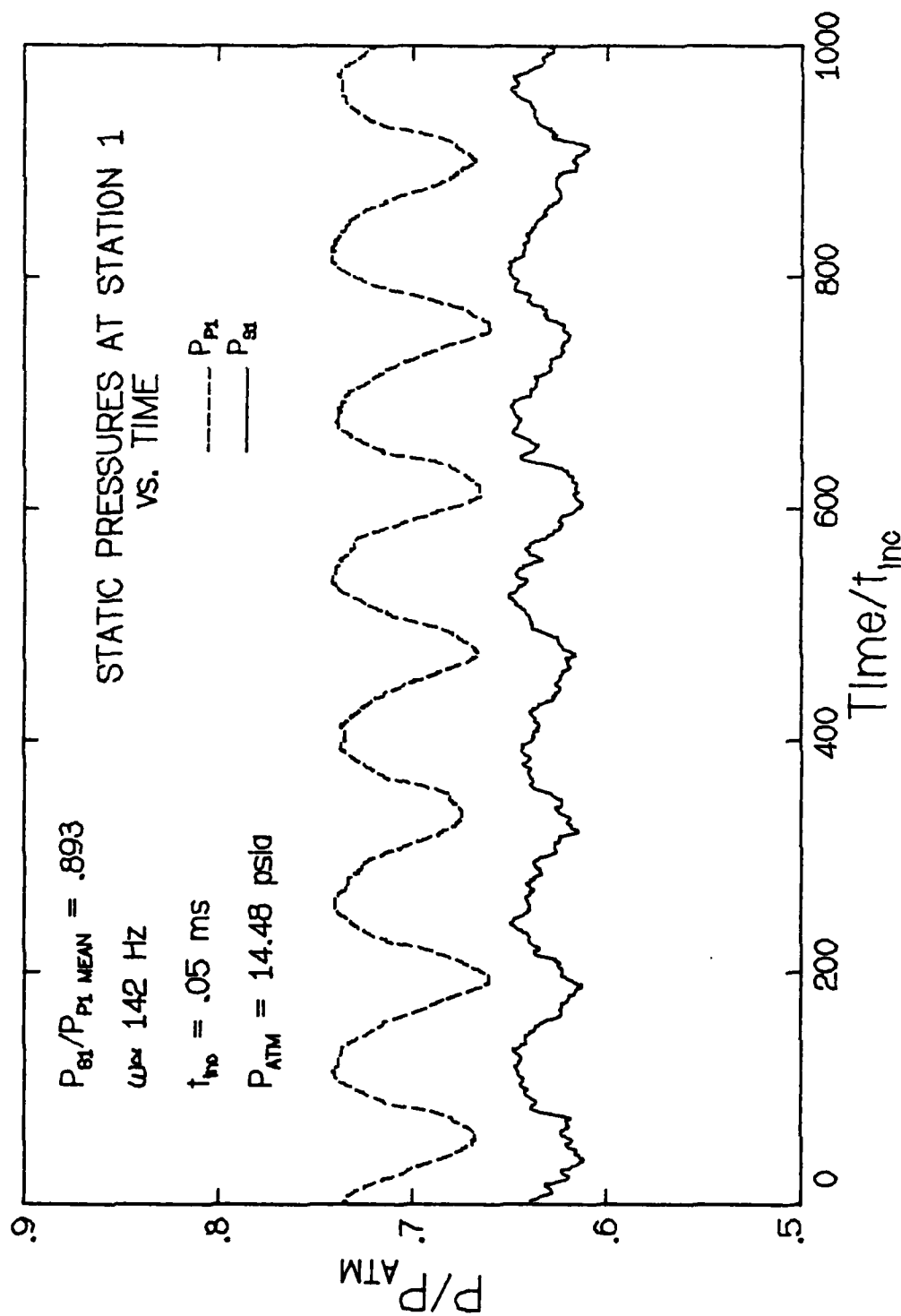


Figure 3.3.2-27 Static pressures at Station 1 versus time  
 ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .160$ )

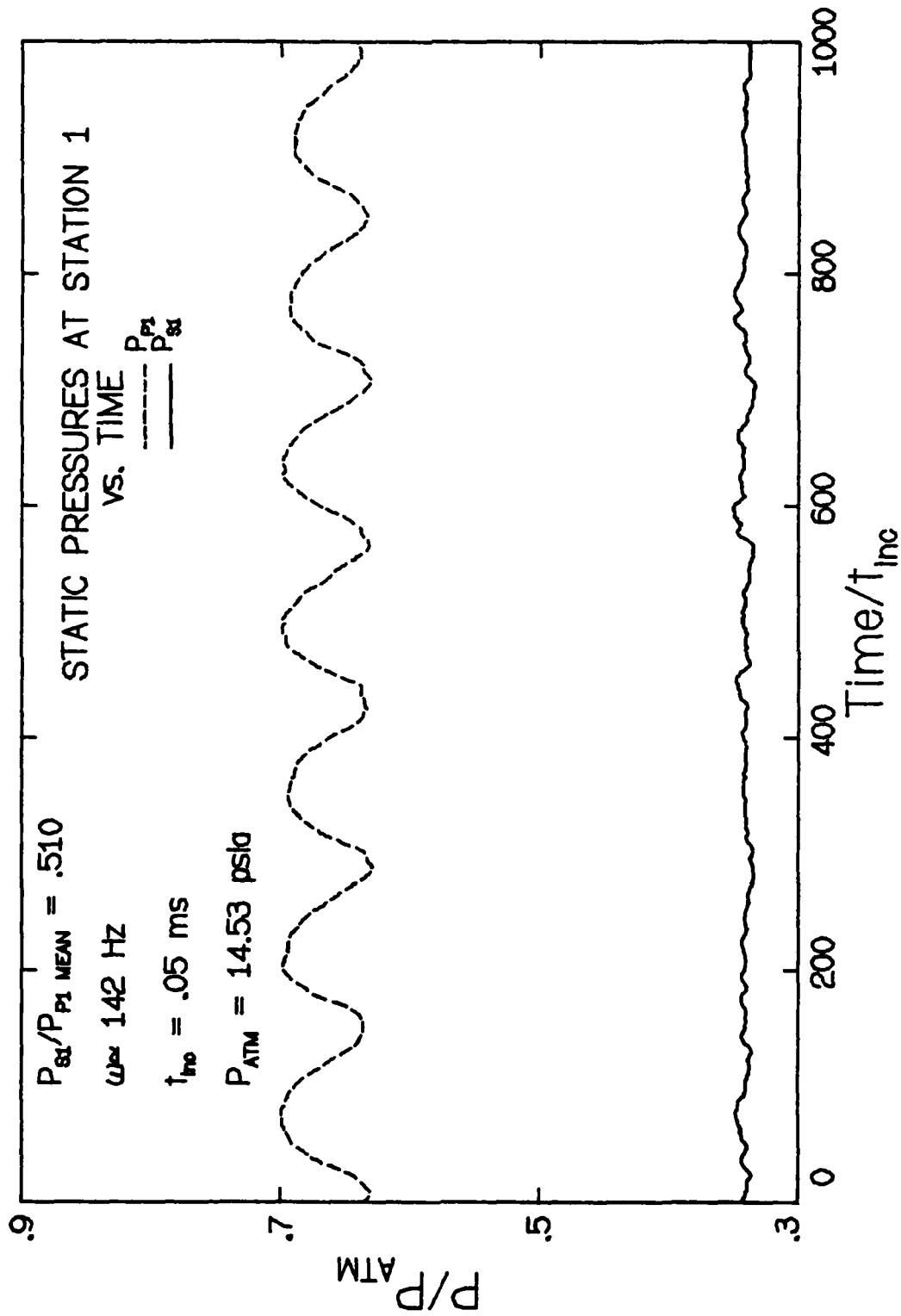


Figure 3.3.2-28 Static pressures at Station 1 versus time  
 ( $L/W = 13.0$ ,  $P_{s0}/P_{p0} \approx .070$ )

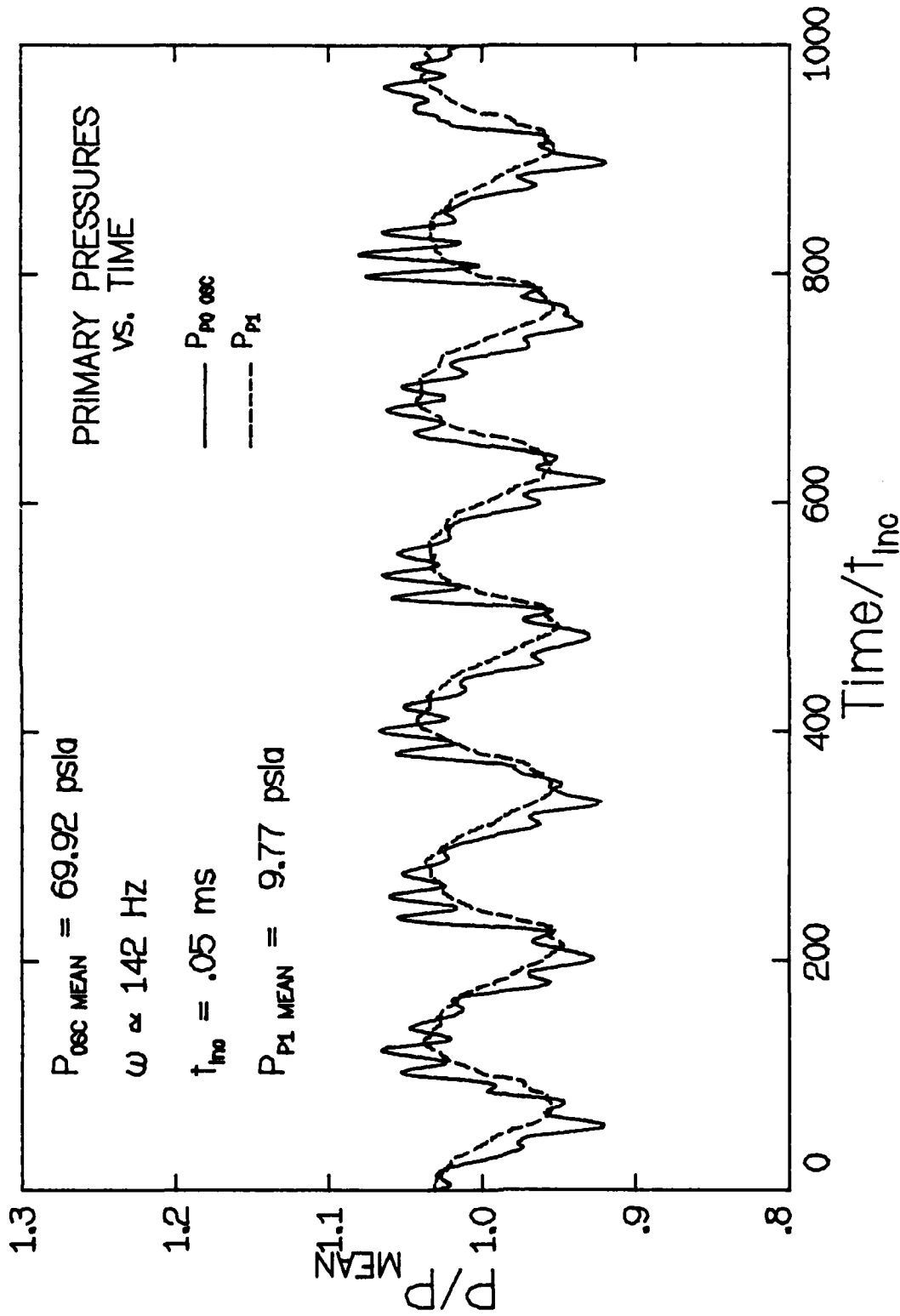


Figure 3.3.2-29 Simultaneously recorded values of  $P_{P1}$  and  $P_{p0}$  versus time at the 142 Hz driver frequency

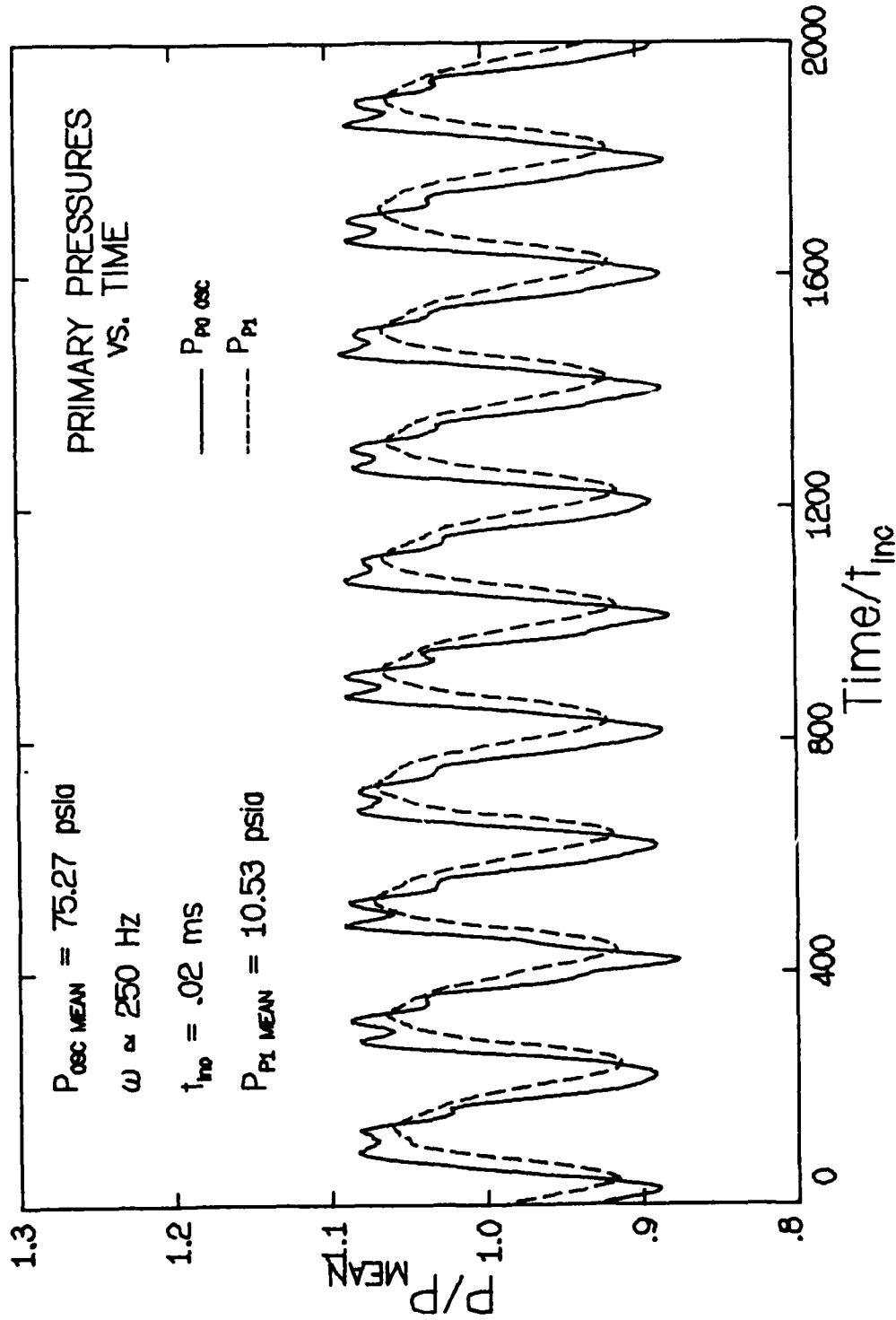


Figure 3.3.2-30 Simultaneously recorded values of  $P_{p1}$  and  $P_{p0}$  versus time at the 250 Hz driver frequency

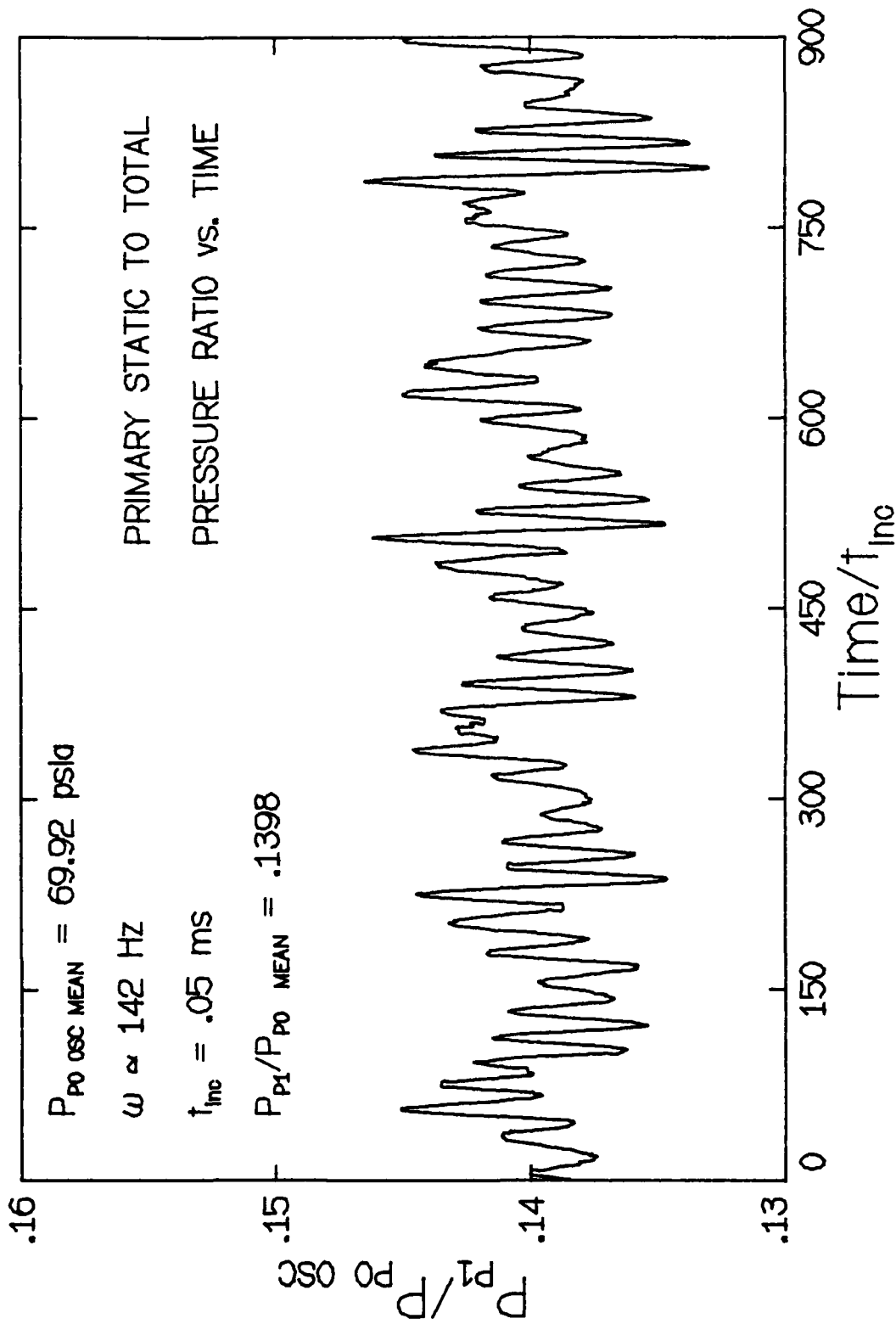


Figure 3.3.2-31  $P_{P1}/P_{P0}$  versus time at the 142 Hz driver frequency

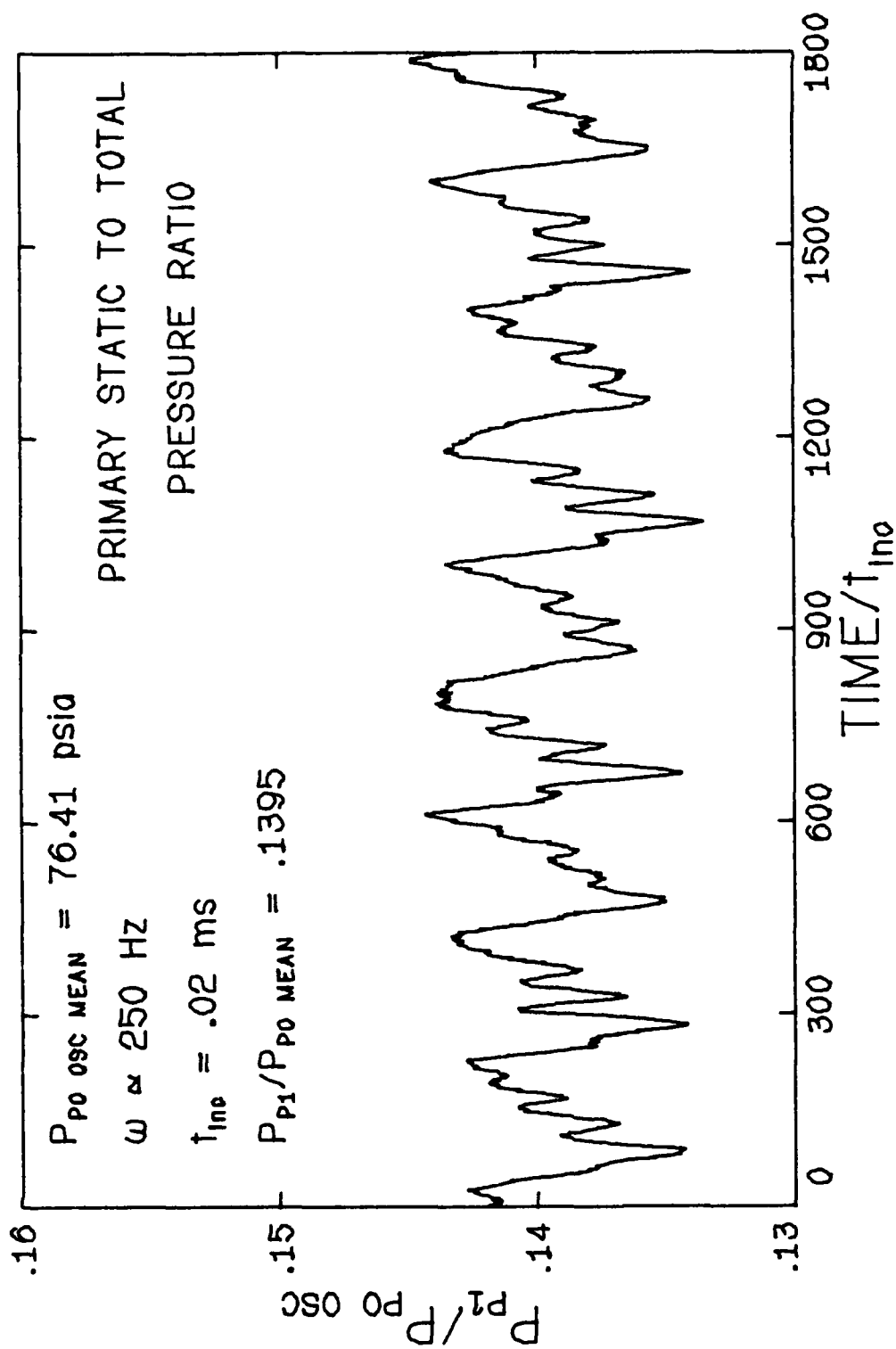


Figure 3.3.2-32  $P_{p1}/P_{p0}$  versus time at the 250 Hz driver frequency

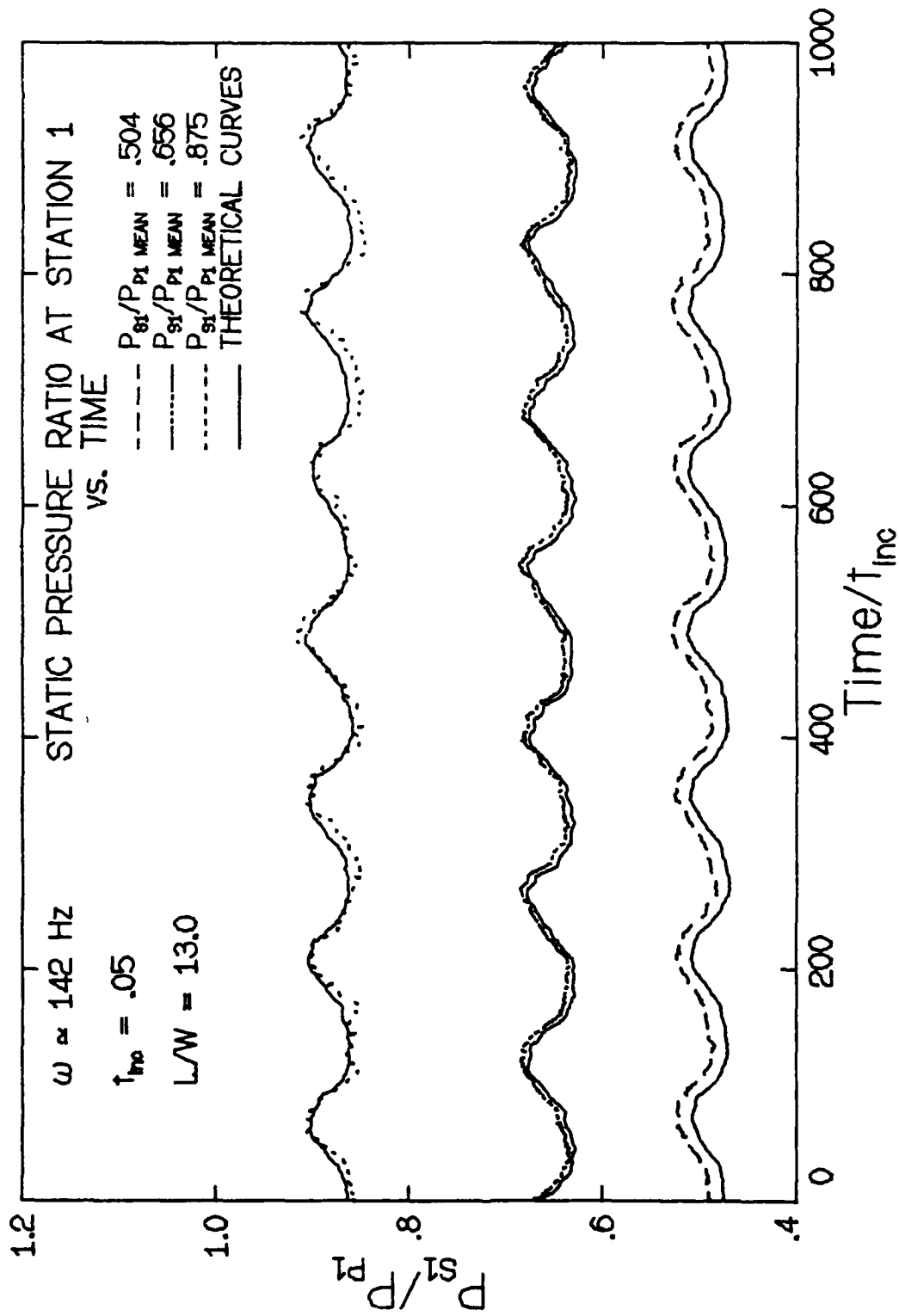


Figure 3.3.2-33 Theoretical and experimental values of  $P_{s1}/P_{p1}$  versus time

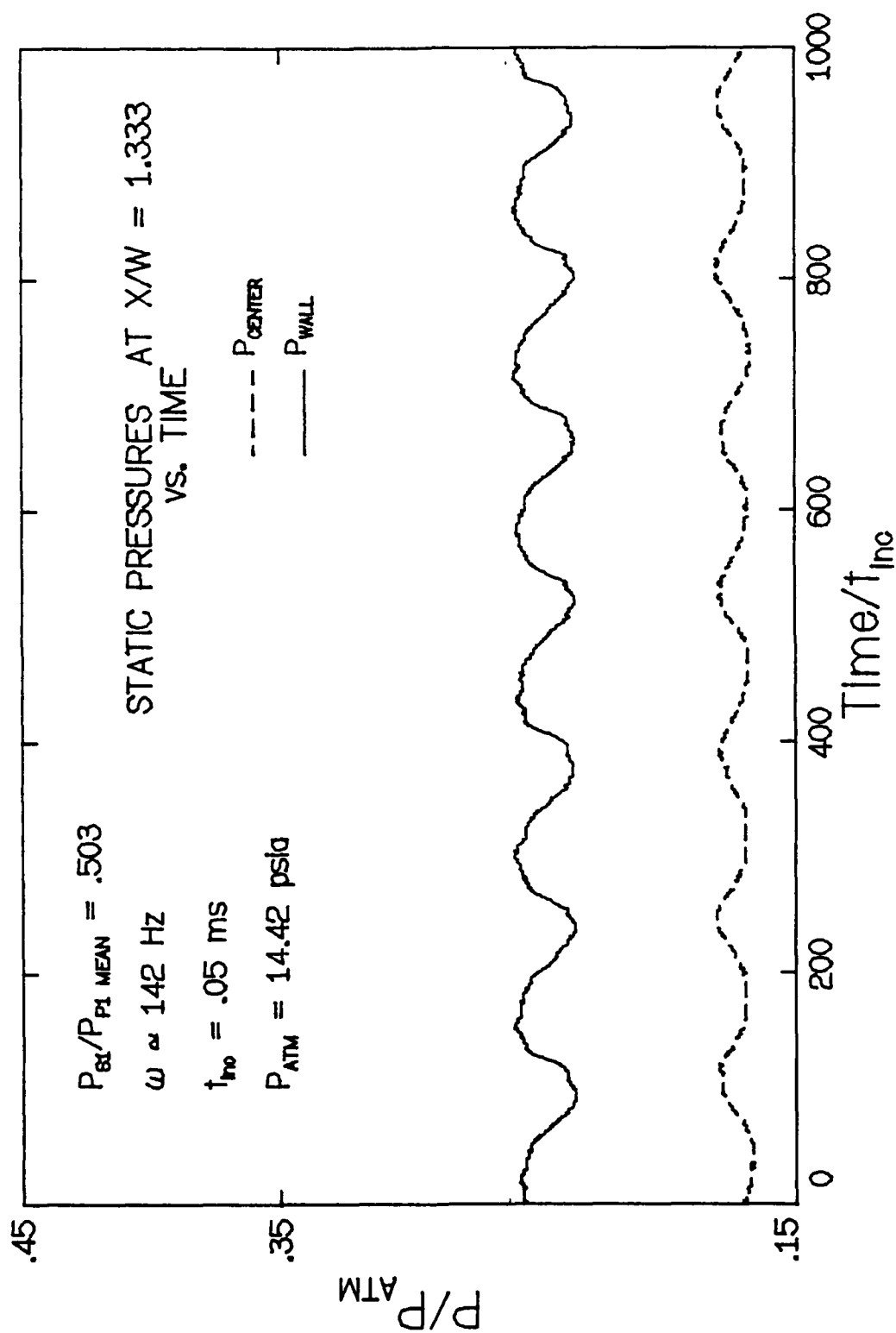


Figure 3.3.2-34 Static pressures versus time at  $X/W = 1.333$  with a relatively low back pressure ( $L/W = 13.0$ ,  $P_{s0}/P_{p0} \approx .070$ )

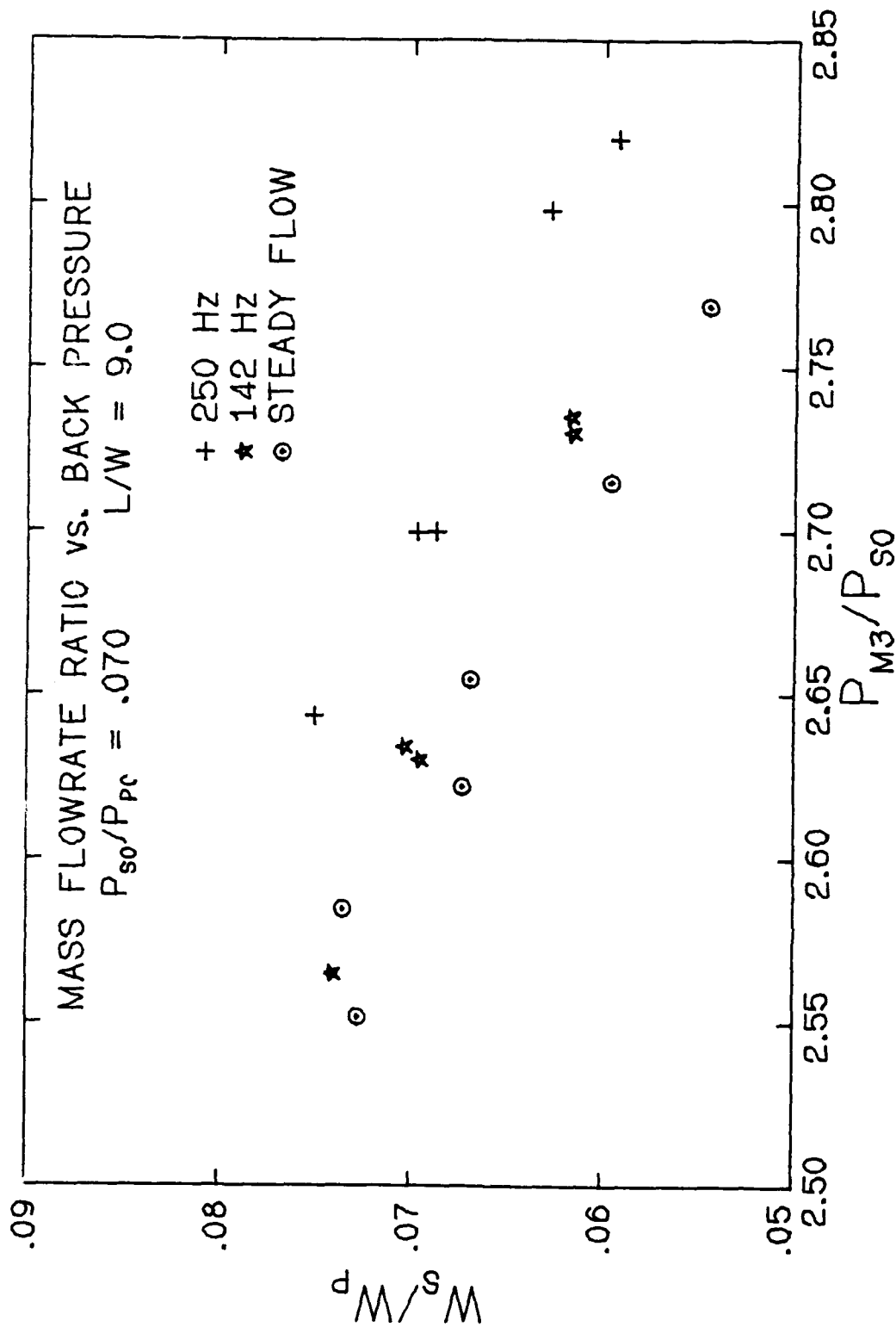


Figure 3.3.2-35  $w_s/w_p$  versus  $P_{m3}/P_{s0}$  for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .070$ )

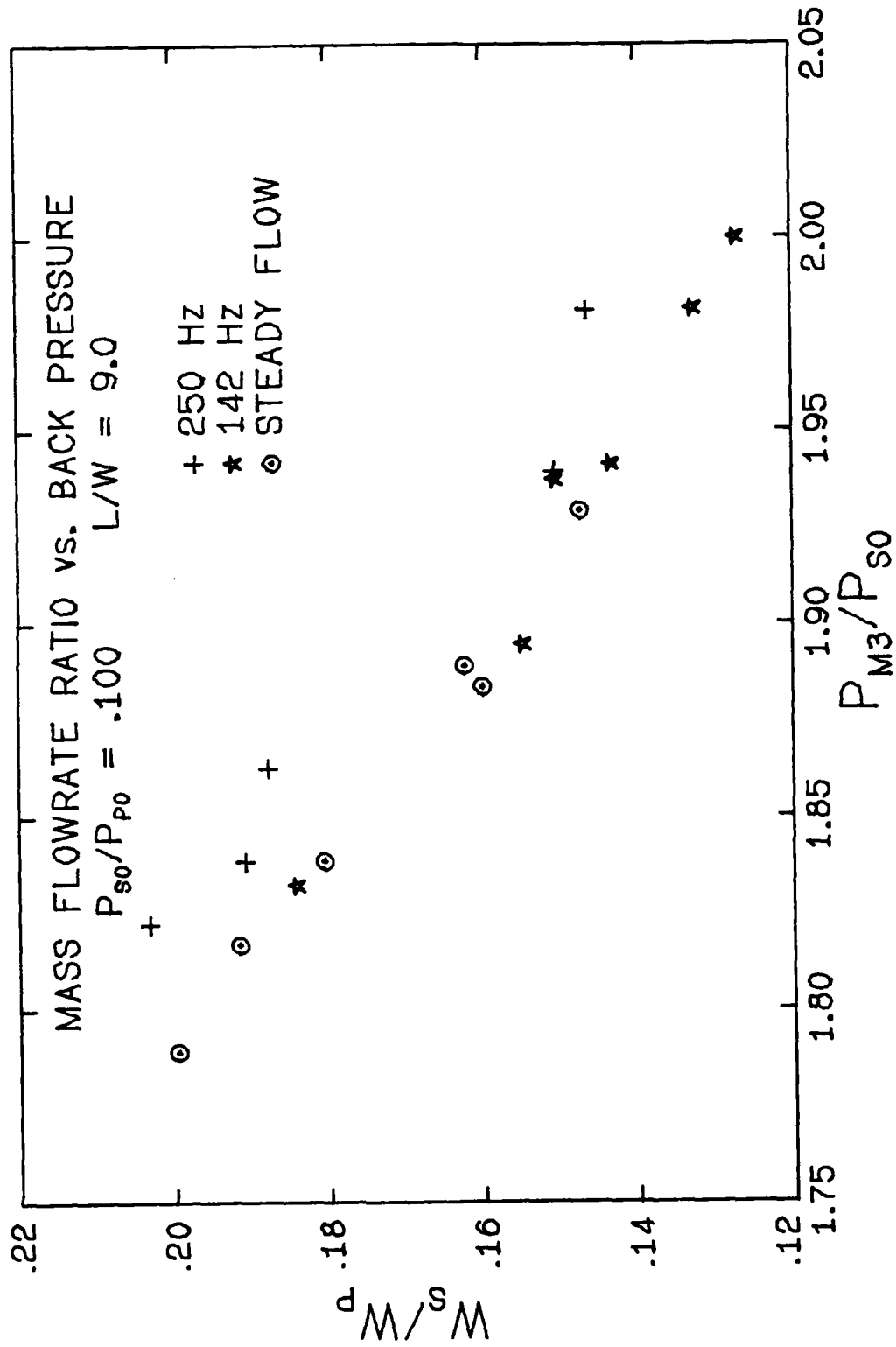


Figure 3.3.2-36  $w_s/w_p$  versus  $P_{M3}/P_{S0}$  for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} = .100$ )

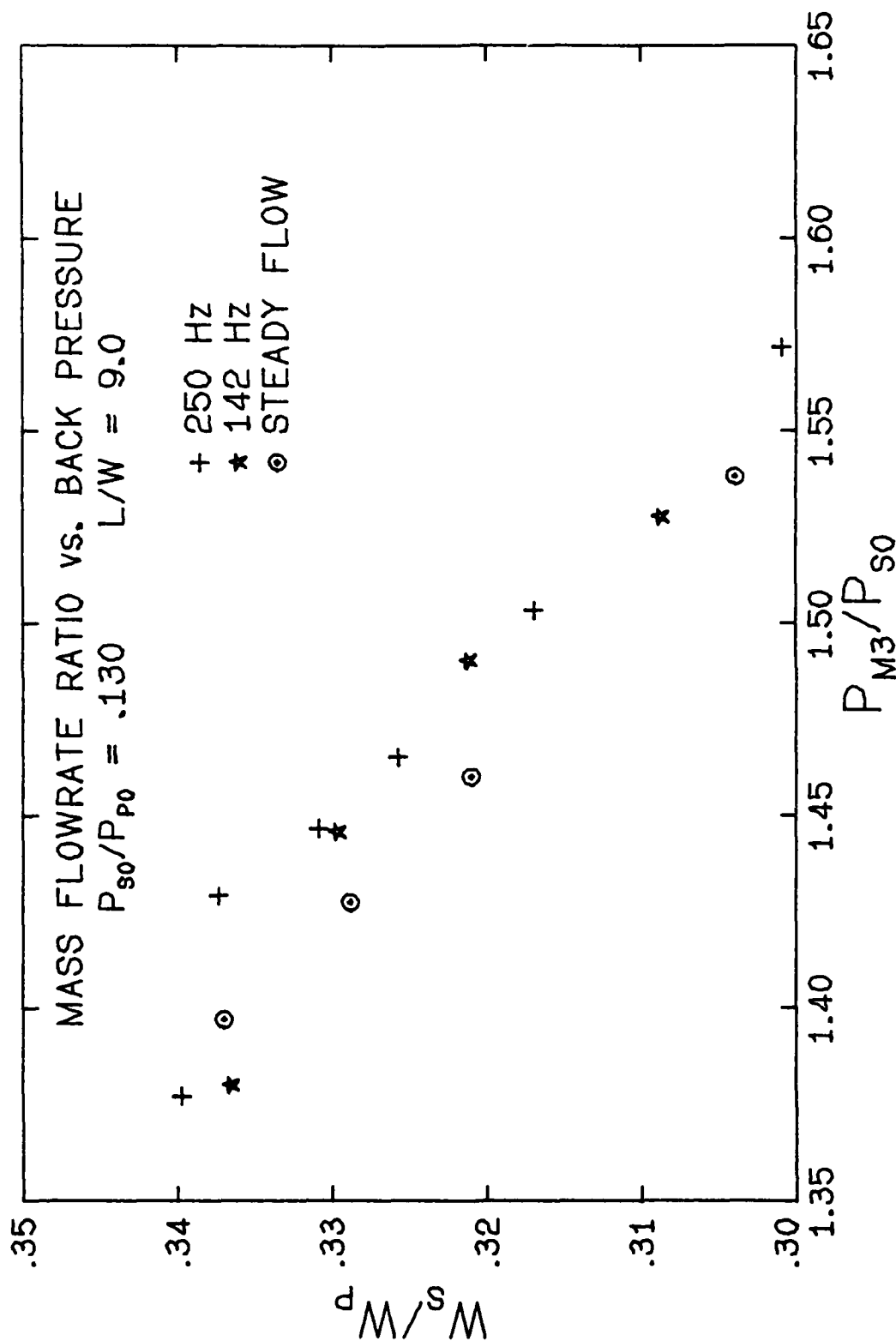


Figure 3.3.2-37  $w_s/w_p$  versus  $P_{M3}/P_{S0}$  for flows that have passed the break-off point and are in the mixed regime ( $L/W = 9.0$ ,  $P_{s0}/P_{p0} \approx .130$ )

## 4.0 CONCLUSIONS

The conclusions that can be drawn as a result of this experimental and theoretical investigation of multiple ducted streams with a steady or a periodic supersonic driver flow are:

1. The one-dimensional analysis predicts the back pressure independent values of  $w_s/w_p$  and  $P_{s1}/P_{p1}$  for the steady driver ejector flow reasonably well over the range of values of  $P_{s0}/P_{p0}$  and mixing duct lengths investigated.
2. The values of the back pressure ratio,  $P_{n3}/P_{s0}$ , at which both steady and periodic driver ejector flows began to break-off from back pressure independent SR flow to MR flow were 25 to 35 percent lower than theoretically predicted.
3. Periodic primary ejector flows were found to drive and determine the secondary flow in such a way that the quasi-steady assumption appears to be valid. Theoretical and experimental values of  $P_{s1}/P_{p1}$  versus time were in reasonably good agreement. Back pressure independent values of the mass flowrate ratios for the periodic driver ejector flows were in good agreement with the mean values predicted by the quasi-steady analysis. The steady flow values of the mass flowrate ratios at the corresponding mean values of  $P_{s0}/P_{p0}$  were nearly the same as the periodic driver flow values.

4. Mass flowrate ratios and pressure recovery capabilities of the ejector were nearly the same for the  $L/W = 16.374$  and  $L/W = 13.0$  mixing ducts. The  $L/W = 9.0$  mixing duct flow broke-off from SR to MR flow at lower values of the back pressure ratio than flow in the longer two mixing ducts. Mass flowrate ratios were less in the shortest mixing duct at given values of  $P_{s0}/P_{p0}$  and  $P_{m3}/P_{s0}$  than in the two longer mixing ducts.
5. Periodic driver ejector flows subject to back pressures high enough to have caused break-off from SR to MR flow operated at higher  $P_{m3}/P_{s0}$ , up to 5 percent higher than the steady flow ejector, at given values of  $P_{s0}/P_{p0}$  and  $w_s/w_p$  in the  $L/W = 9.0$  mixing duct. Explained another way, one might say that higher mass flowrate ratios were obtained at given values of  $P_{s0}/P_{p0}$  and  $P_{m3}/P_{s0}$  for ejector flows that had passed the break-off point and were in the mixed regime. However, this is not felt to be the result of increased entrainment due to the periodicity of the driver but rather due to a shift in the position, towards the SR break-off point, that the ejector operates at on the MR solution surface, see Fig. 2.1-2, for a given value of  $P_{s0}/P_{p0}$ . The agreement between steady and periodic driver flow back pressure independent mass flowrate ratios, the quasi-steady nature of the periodic ejector flows at Station 1, and the

linearity of the theoretical values of  $w_s/w_p$  as a function of  $P_{s0}/P_{p0}$ , see Fig. 3.3.1-2, suggests that the entrainment of the secondary flow in the mixed regime near break-off with the supersonic regime is not significantly affected by the periodicity of the driver flow.

6. Static pressure measurements versus time did not indicate that significant differences in the pressure recovery process or flow characteristics within the mixing duct existed between periodic and steady driver ejector flows. Shock waves in the supersonic primary flow were greatly disturbed by a periodic driver but the shock waves in the steady driver ejector flow were also quite transient and unstable. Mean values of static pressures at the same location and under corresponding flow conditions were approximately the same in periodic and steady driver ejector flows.
7. Mixing rates between the primary and secondary flows were not noticeably altered by a periodic driver. The location of the point at which the static pressures became nearly uniform across the mixing duct was approximately the same for periodic and steady driver ejector flows. Exit plane stagnation pressure uniformity was slightly improved in only a few cases by a periodic driver flow. It appears that rapid mixing did not take

place until the primary flow in the center of mixing duct became subsonic. As indicated by the presence of shock waves, the periodicity of the primary flow did not change the average location of the disintegration of the supersonic primary to subsonic flow. The periodic driver had little effect on the character of the flow in the high mixing rate region which lies between the approximate location of the loss of the supersonic primary flow and the exit plane of the mixing duct.

8. The Strouhal number of the periodic driver ejector flows were low in comparison to those in the mixing studies cited in Section 1.2. If based on the velocity of the primary flow at Station 1, the hydraulic diameter of the primary flow C-D nozzle, and the 250 Hz driver frequency, the Strouhal number is  $St = .0064$ . The Strouhal number for a subsonic secondary stream at Station 1 with the theoretical flow velocity at  $P_{s0}/P_{p0} = .100$  and with  $\omega = 250$  Hz is  $St = .025$ . With the theoretical value of  $M_{m3}$  for  $P_{s0}/P_{p0} = .100$  and the mixing duct hydraulic diameter, the Strouhal number at the exit plane is  $St = .029$  with  $\omega = 250$  Hz. A fluid particle will pass entirely through the mixing duct in only a fraction of a driver cycle. The driver flow frequencies used in this

investigation were too low to significantly effect the dynamics of mixing between high speed compressible streams in a short mixing duct.

9. The large-scale fluidic oscillator was an efficient and reliable method of producing periodic pulses. It is not felt that frequencies higher than approximately 500 Hz could be obtained with a fluidic oscillator configuration similar to one used in this investigation without decreasing the size of the oscillator to such an extent that the mass flowrate through the device must be appreciably decreased.
10. The transient disturbances in the steady driver ejector flows were comparable to disturbances produced by the periodic driver in most cases; thus, the effects of a periodic driver on ejector flow have not been clearly delineated by the "steady" flow comparison. An axisymmetric ejector configuration may prove to be more stable than 2-D planar configuration examined and may therefore provide a more meaningful comparison.

## 5.0 REFERENCES

1. Ejectors, von Karman Institute, Lecture Series 79, two volumes, 1975, Addy, A. L., "The Analysis of Supersonic Ejector Systems"; Delery, J., "Methods d'étude des éjecteurs Supersonic Application aus tuyères double-flux;" Olivari, D., "Jets and Mixing Phenomena"; Viets, H., "Thrust Augmenting Ejectors"; Walker, B. J., "Chemical Laser Pumping Systems"; Schmitt, H., "Summary of Possible Applications and Present Status of Various Ejector Techniques."
2. Brown, S. L. and Murphy, R. D., "Design and Testing of Thrust Augmenting Ejectors," V/STOL Aerodynamics, AGARD-CP-143, 1974.
3. DeJoode, A. D. and Pantankar, S. V., "Prediction of Three-Dimensional Turbulent Mixing in an Ejector," AIAA Journal, Vol. 16, February 1978, pp. 145-150.
4. Viets, H., "Thrust Augmenting Ejector Analogy," Journal of Aircraft, Vol. 14, April 1977, pp. 409-411.
5. Gilbert, G. B. and Hill, P. G., "Analysis and Testing of Two-Dimensional Slot Nozzle Ejectors with Variable Area Mixing Sections," NASA CR-2251, May 1975.
6. Hasinger, S. H., "Performance Characteristics of Ejector Devices," former Aerospace Research Laboratories, Wright-Patterson Air Force Base, Technical Report ARL TR 75-205, June 1975.
7. Tai, T. C., "Analysis and Design of Thrust Augmenting Ejectors," Prediction Methods for Jet V/STOL Propulsion Aerodynamics, Vol. 2, M. F. Platzer (editor), Proceedings of a Naval Air Systems Command Research and Technology Group Workshop, Institute for Defense Analysis, Arlington, Virginia, July 28-31, 1975, pp. 702-721.
8. Addy, A. L. and Mikkelsen, C. D., "An Investigation of Gas Dynamic Flow Problems in Chemical Laser Systems," Department of Mechanical and Industrial Engineering, University of Illinois at Urbana, Report No. UILU-ENG-74-4009, 1974.
9. Fabri, J. and Paulon, J., "Theory and Experiments on Supersonic Air-to-Air Ejectors," NACA TM 1410, September 1958.
10. Chow, W. L. and Addy, A. L., "Interaction Between Primary and Secondary Streams of Supersonic Ejector Systems and their Performance Characteristics," AIAA Journal, Vol. 2, April 1964, pp. 686-695.
11. Addy, A. L., "The Analysis of Supersonic Ejector Systems," Supersonic Ejectors, AGARD-CP-163, 1972, pp. 31-101.

PRECEDING PAGE BLANK - NOT FILMED

12. Chow, W. L. and Yeh, P. S., "Characteristics of Supersonic Ejector Systems with Non-Constant Area Shroud," AIAA Journal, Vol. 3, March 1965, pp. 525-527.
13. Mikkelsen, C. D., Sandberg, M. R., and Addy, A. L., "Theoretical and Experimental Analysis of the Constant Area Supersonic-Supersonic Ejector," Department of Mechanical and Industrial Engineering, University of Illinois at Urbana, Report No. UILU-ENG-76-4003, 1976.
14. Baker, L. R., Jr. and McDermit, J. H., "Survey of Pressure Recovery Methods for Chemical Laser Applications," Chemical Laser Analysis and Development, Vol. VI, Lockheed Missile and Space Co., Technical Report RK-CR-73-2, October 1973.
15. Townsend, A. A., "The Mechanisms of Entrainment in Free Turbulent Flows," Journal of Fluid Mechanics, Vol. 26, Part 4, 1966, pp. 689-716.
16. Kovaszney, L. S. G., "The Structure of Turbulence in Shear Flows," AGARD-CP-93, 1971.
17. Brown G. and Roshko, A., "The Effect of Density Differences on the Turbulent Mixing Layer," Journal of Fluid Mechanics, Vol. 64, Part 4, 1974, pp. 775-816.
18. Roshko, A., "Structure of Turbulent Shear Flows: A New Look," AIAA Journal, Vol. 14, October 1976, pp. 1349-1357.
19. Bradshaw, P., "Interacting Shear Layers in Turbomachines," Turbulence in Internal Flows, Murthy, S. N. B. (editor), A Project SQUID Workshop, Warrenton, Virginia, June 14-15, 1976, pp. 35-65.
20. Dimotakis, P. E. and Brown, G. L., "The Mixing Layer at High Reynolds Numbers: Large Structure Dynamics and Entrainment," Journal of Fluid Mechanics, Vol. 76, Part 3, 1976, pp. 535-560.
21. Bevilaqua, P. M. and Lykoudis, P. S., "Mechanisms of Entrainment in Turbulent Wakes," AIAA Journal, Vol. 9, 1971, pp. 1657-1659.
22. Papailiou, D. D. and Lykoudis, P. S., "Turbulent Vortex Streets and Entrainment," Journal of Fluid Mechanics, Vol. 62, Part 1, 1974, pp. 11-31.
23. Crow, S. C. and Champaign, F. H., "Orderly Structure in Jet Turbulence," Journal of Fluid Mechanics, Vol. 48, Part 3, 1971, pp. 547-591.
24. Becker, H. A. and Massoro, T. A., "Vortex Evolution in a Round Jet," Journal of Fluid Mechanics, Vol. 31, Part 3, 1968, pp. 435-448.

25. Glass, D. R., "Effects of Acoustic Feedback on the Spread and Decay of Supersonic Jets," AIAA Journal, Vol. 6, October 1968, pp. 1890-1897.
26. McCormack, P. D., Cochran, D., and Crane, L., "Periodic Vorticity and Its Effect on Mixing," The Physics of Fluids, Vol. 9, August 1966, pp. 1555-1560.
27. Binder, G. and Favre-Marinet, M., "Mixing Improvement in Pulsating Turbulent Jets," Fluid Mechanics of Mixing, ASME, Symposium Proceedings of the Joint Meeting, Georgia Institute of Technology, June 20-22, 1973, pp. 167-172.
28. Bremhorst, K. and Harch, W. H., "Near Field Velocity Measurements in a Fully Pulsed Subsonic Air Jet," Turbulent Shear Flows, Symposium Proceedings, Pennsylvania State University, April 18-20, 1977, pp. 2.41-2.50.
29. Olivari, D., "Analysis of an Axisymmetrical Turbulent Pulsating Jet," von Karman Institute Technical Note No. 104, November 1974.
30. Viets, H., "Flip-Flop Jet Nozzle," AIAA Journal, Vol. 13, October 1975, pp. 1375-1379.
31. Platzer, M. F., Simmons, J. M., and Bremhorst, K., "Entrainment Characteristics of Unsteady Subsonic Jets," AIAA Journal, Vol. 16, No. 3, March 1978, p. 282.
32. Johnson, J. K., Jr., "An Analytical and Experimental Investigation of Ejector Performance for Nonsteady Flow Conditions," Clemson University, College of Engineering, Engineering Experiment Station Bulletin 107, July 1966.
33. Johnson, W. S. and Yang, T., "A Mathematical Model for the Prediction of the Induced Flow in a Pulsejet Ejector with Experimental Verification," ASME Paper No. 68-WA/FE-33, 1968.
34. Johnson, W. S., "A Performance Comparison of the Wave Energy Exchanger and the Steady Flow Ejector," Ph.D. Thesis, University of Tennessee, Mechanical and Aerospace Engineering Department, 1967.
35. Khare, J. M., "An Analytical and Experimental Investigation of an Unsteady Flow Ejector," University of Calgary, Mechanical Engineering Department, Report No. 53, 1973.
36. Quinn, B., "Interactions Between Screech Tones and Ejector Performance," Journal of Aircraft, Vol. 14, May 1977, p. 467.
37. Zarek, J. M., "The Neglected Parameters in Pulsating Flow Measurement," ASME, Flow Measurement Symposium, K. C. Cotton (editor), Pittsburg, Pennsylvania, September 26-28, 1966.

38. Sparks, C. R., "A Study of Pulsating Effects on Orifice Metering of Compressible Flow," ASME, Flow Measurement Symposium, K. C. Cotton (editor), Pittsburg, Pennsylvania, September 26-28, 1966.
39. Ower, E. and Pankhurst, R. C., The Measurement of Air Flow, Pergamon Press, New York, Oxford, 4th edition, 1966, pp. 323-333.
40. Loh, W. H. T., "Theory of the Hydraulic Analogy for Steady and Unsteady Gas Dynamics," Modern Developments in Gas Dynamics, W. H. T. Loh (editor), Plenum Press, New York, 1969.
41. Halbach, C. R., Otsap, B. A., and Thomas, R. A., "A Pressure Insensitive Fluidic Temperature Sensor," Advances in Fluidics, ASME, Brown, F. T. (editor), 1967, pp. 293-312.
42. Stover, T. R., "Development of a Large-Scale Fluidic Oscillator for Application to an Unsteady Aerodynamic Ejector System Using the Hydraulic Analogy," Masters Thesis, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana, 1978.
43. Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1, Ronald Press Co., New York, 1953.
44. Telionis, D. P., "Unsteady Boundary Layers, Separated and Attached," Unsteady Aerodynamics, AGARD-CP-227, September 1977.
45. Simpson, R. L., "Features of Unsteady Turbulent Boundary Layers as Revealed from Experiments," Unsteady Aerodynamics, AGARD-CP-227, September 1977.
46. Rudinger, G., Nonsteady Duct Flow: Wave Diagram Analysis, Dover Publications Inc., New York, 1969, pp. 94-106.
47. Nelson, J. R., "Investigation of the Mixing Region Between the Primary and Secondary Streams of a Two-Dimensional Supersonic Air-Air Ejector System," Masters Thesis, Air Force Institute of Technology, Air University, June 1966.

## APPENDIX A

UCAE, Unsteady Constant Area Ejector program, was written to perform the quasi-steady, one-dimensional analysis discussed in Section 2.0. The program and a sample input and output are listed in this appendix.

Default values of UCAE assume air-to-air ejector flow with equivalent primary and secondary stagnation temperatures. Variable definitions are given at the beginning of the program. MP1, AP1M3, PM3SOI, and MMAX are not assigned default values and must be assigned values in the first NAMELIST input to the program. An arbitrary sinusoidal curve, PSOPOI(time), as described near the beginning of the program, is available for use as the source of the calculation parameter, PSOPOI. This is the default form of the PSOPOI(time) parameter and is a rough approximation of the experimental periodic flow. The NAMELIST input to the program must include CURVE = .FALSE. if PSOPOI(time) data is to be read from a data file. Input file TAPE5 must include all input data, both the NAMELIST variables and, if CURVE = .FALSE., the PSOPOI data.

The program output, to output file TAPE6, includes input conditions and averages of ejector performance parameters. Output of performance parameter values at each time increment is the default form of the output and can be suppressed by including OUT = .FALSE. in the NAMELIST input. The value of MS1 at which the supersonic regime breaks-off with the approximate regime, MCRIT, and the corresponding stagnation pressure ratio, PCRIT, are written onto the output file TAPE6 for each data set read into the program. PS1P1 is written onto TAPE7 at each time increment. This feature was used to obtain a theoretical PS1P1 versus time curve to compare with experimental results.

Time is normalized by the time increment between successive PSOP01 data points.

## A.1 UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
MAIN PROGRAM

```

C      PROGRAM UCAE(INPUT,OUTPUT,TAPE7,TAPE5=INPUT,TAPE6=OUTPUT)
C      UNSTEADY CONSTANT AREA EJECTOR INTEGRATION PROGRAM
C
C      THIS PROGRAM CALCULATES THE ONE-DIMENSIONAL THEORETICAL MEAN VALUES
C      OF THE EJECTOR/DUCTED MULTIPLE STREAMS PERFORMANCE PARAMETERS FOR THE
C      GEOMETRIC AND FLOW BOUNDARY CONDITIONS INPUT. A PSOPO=PSOPO(TIME)
C      CURVE IS TO BE THE SOURCE OF THE CALCULATION PARAMETER, PSOPO. THE
C      CURVE IS SUBDIVIDED INTO STEPS OR SLUGS IN TIME AND THE ANALYSIS IS
C      PERFORMED ON EACH STEP TO DETERMINE THE AVERAGE VALUES OF THE PER-
C      FORMANCE PARAMETERS OF INTEREST. THE PSOPO(TIME) CURVE CAN BE INPUT
C      VIA DATA FILE OR AN ARBITRARY SINUSOIDAL CURVE IS AVAILABLE. TIME
C      IS NORMALIZED BY THE SAMPLING TIME INCREMENT.
C
C      *****
C
C      VARIABLE DEFINITIONS AND THEIR DEFAULT VALUES:
C      SOME VARIABLE DEFINITIONS.
C
C      GS,GP.... THE RATIO OF SPECIFIC HEATS OF THE SECONDARY AND
C                PRIMARY FLUIDS.
C      MWSP..... THE SECONDARY TO PRIMARY MOLECULAR WEIGHT RATIO.
C      TSOPO.... THE SECONDARY TO PRIMARY STAGNATION TEMPERATURE RATIO.
C      MP1..... THE PRIMARY FLOW MACH AT STATION 1.
C      MS1..... THE SECONDARY FLOW MACH NUMBER AT STATION 1.
C      MM3..... THE MIXED FLOW MACH NUMBER AT STATION 3.
C      MMAX..... THE MAXIMUM MACH NUMBER THAT THE PRIMARY FLOW CAN ATTAIN
C                WITHIN THE MIXING SECTION AS A RESULT OF A ONE DIMENSIONAL
C                ISENTROPIC EXPANSION.
C      PM3SOI... INPUT VALUE OF THE BACK PRESSURE CONDITION, RATIO OF THE
C                MIXED FLOW EXIT PLANE STATIC TO SECONDARY STAGNATION
C                PRESSURE.
C      PMOSO.... THE RATIO OF MIXED TO SECONDARY FLOW STAGNATION PRESSURES.
C      PS1P1.... THE RATIO OF SECONDARY TO PRIMARY FLOW STATIC PRESSURES AT
C                STATION 1.
C      PSOPO.... THE SECONDARY TO PRIMARY STAGNATION PRESSURE RATIO.
C      AP1M3.... THE RATIO OF THE PRIMARY TO TOTAL FLOW AREAS.
C      NCASE.... A DATA SET COUNTER.
C
C      DEFAULT VALUES OF THE INPUT VARIABLES.
C
C      GS(1.4),GP(1.4),MWSP(1.0),TSOPO(1.0),MP1(),PM3SOI(),MMAX(),AP1M3()
C
C      LOGICAL VARIABLES, THEIR FUNCTIONS AND DEFAULT VALUES.
C
C      NEW..... .TRUE. IS REQUIRED EACH TIME THE DATA SET HAS A DIFFERENT
C                MP1, AP1M3, GS, OR GP THAN THE PREVIOUS SET. TO AVOID
C                CALCULATING MCRT WHEN NO CHANGES OCCUR IN THESE VARIABLES,
C                NEW=.FALSE. SHOULD BE INPUT. .TRUE. IS THE DEFAULT VALUE.
C
C      OUT..... CAUSES OUTPUT FOR EACH TIME STEP WHEN .TRUE. IS THE INPUT.
C                .FALSE. SHOULD BE USED IF CYCLE AVERAGES AND CASE INPUT
C                DATA ARE THE ONLY OUTPUT DESIRED.
C
C      CURVE.... IF AN ARBITRARY SINUSOIDAL PSOPO(T) CURVE IS TO BE USED,
C                .TRUE. MUST BE THE INPUT. THIS IS THE DEFAULT, FOR WHICH:
C
C                AMP=.100, THE AMPLITUDE.
C                PAVG=.100, THE MEAN PSOPO.
C                NCYC=10, THE NUMBER OF TIME STEPS PER CYCLE.

```

UCA001  
UCA002  
UCA003  
UCA004  
UCA005  
UCA006  
UCA007  
UCA008  
UCA009  
UCA010  
UCA011  
UCA012  
UCA013  
UCA014  
UCA015  
UCA016  
UCA017  
UCA018  
UCA019  
UCA020  
UCA021  
UCA022  
UCA023  
UCA024  
UCA025  
UCA026  
UCA027  
UCA028  
UCA029  
UCA030  
UCA031  
UCA032  
UCA033  
UCA034  
UCA035  
UCA036  
UCA037  
UCA038  
UCA039  
UCA040  
UCA041  
UCA042  
UCA043  
UCA044  
UCA045  
UCA046  
UCA047  
UCA048  
UCA049  
UCA050  
UCA051  
UCA052  
UCA053  
UCA054  
UCA055  
UCA056  
UCA057  
UCA058  
UCA059  
UCA060

```

C      ARE THE DEFAULT VALUES.
C      IF A PSOPO(T) CURVE IS TO BE READ FROM A DATA FILE, .FALSE.
C      MUST BE INPUT.
C
C      OUTPUT DATA:
C
C      ALL DATA INPUT, CYCLE MEAN VALUES OF NS1, PS1P1, NM3, PSOPO, PHOSO,
C      AND WSP. NOTE THAT OUT=.TRUE. WILL CAUSE THE ABOVE TO BE OUTPUT FOR
C      EACH TIME STEP IN THE PSOPO(TIME) CYCLE AS WELL AS THE BREAK-OFF
C      VALUES OF PH3SO, PHOSO, AND NM3 IN SB, APPH, SSR FLOWS, AND NR
C      FLOW SOLUTIONS THAT MEET THE BACK PRESSURE CONDITION.
C
C      *****
C
C      MUCH OF THIS PROGRAM COMES DIRECTLY FROM CAE, CONSTANT AREA EJECTOR
C      PROGRAM, USED IN "AN INVESTIGATION OF GAS-DYNAMIC FLOW PROBLEMS IN
C      CHEMICAL LASER SYSTEMS", ADDY, A. L. AND MIKKELSON, C. D.,
C      UNIVERSITY OF ILLINOIS REPORT UIU-ENG-74-4009, 1974.
C
C      *****
C
C      COMMON/BLOCK1/GP,GS,HP1,WSP,TSOPO,AP1M3,MNIN,NEW,MNAX,
C      &PCRT
C      COMMON/BLOCK2/NS1,NM3,PS1P1,PHOSO,WSP,PH3SO
C      COMMON/BLOCK3/SHS1,SPHOSO,SHM3,SPSOPO,SPS1P1,SWSP
C      LOGICAL CURVE,NEW,OUT
C      REAL NS1,HP1,MCRT,WSP,M,NM3,MNIN,MNAX
C
C      NAMELIST/IUCAR/GS,GP,WSP,TSOPO,AP1M3,HP1,PH3SOI,OUT,NCASE
C      &NEW,MNAX,CURVE,AMP,PAVG,NCYC
C
C      ASSIGN DEFAULT VALUES.
C      DATA GS,GP,WSP,TSOPO,OUT,NEW,NCASE/2*1.4,2*1.,2*.TRUE.,1/
C      DATA CURVE,AMP,PAVG,NCYC/.TRUE.,0.10,0.10,10/
C      NOTE THAT NCASE IS NOT INCREMENTED BY THE PROGRAM.
C
C      PPO(G,M)=(1.0+.5*(G-1.0)*(M**(-G/(G-1.))))
105 IPRESS=0
C      THE VARIABLE, IPRESS, IS THE TIME STEP COUNTER IN THE PROGRAM.
C      INPUT FLOW AND GEOMETRIC CONDITIONS.
C      READ(5,IUCAR)
C      IF(ZOF(5)) 999,110
110 IF(.NOT.NEW) GO TO 115
C      PROGRAM SEEKS THE MAXIMUM NS1 WITH WHICH THE FABRI CHOKING CONDITION
C      CAN BE SATISFIED. THIS IS A FUNCTION OF HP1,AP1M3, AND GP.
C      CALL CRITH(MCRT)
C      THE PSOPO CORRESPONDING TO MCRT IS:
C      PCRT=PPO(GP,HP1)/PPO(GS,MCRT)
C      THE INPUT IS NOW OUTPUT
115 WRITE(6,120)NCASE,GS,GP,WSP,TSOPO,AP1M3,HP1,PH3SOI
120 FORMAT(5(//,10X,"INPUT DATA FOR CASE NO.",I3,///,10X,"GS=",F7.4,
C      8X,"GP=",F7.4,8X,"WSP=",F7.4,///,10X,"TSOPO=",F7.4,5X,"AP1M3=",
C      6F7.4,5X,"HP1=",F7.4,///,10X,"PH3SOI=",F8.4,///)
C      IF(NEW) WRITE(6,125) MCRT,PCRT
125 FORMAT(///,10X,"FOR THIS CASE, MCRT=",F7.4,5X,"PCRT=",F7.4,///)
C
C
C
C

```

# UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE) MAIN PROGRAM

130 CALL PRATIO(AMP,PAVG,NCYC,PSOPOI,IPRESS,CURVE)	UCA121
IF(IPRESS.FQ.NCYC.AND..NOT.CURVE) GO TO 145	UCA122
IF(.NOT.CURVE.OR.IPRESS.GT.1) GO TO 140	UCA123
WRITE(6,135) AMP,PAVG,NCYC	UCA124
135 FORMAT(/,10X,"FOR THE SINUSOIDAL PRESSURE RATIO CURVE:",/,10X,	UCA125
6"AMP=",F7.3,10X,"PAVG=",F7.4,10X,"NCYC=",I5," TIME SLUGS/CYCLE")	UCA126
140 CALL CALCAE(PSOPOI,PHISOI,OUT,IPRESS,NCYC,NERROR,CURVE,HCRT)	UCA127
IF(NERROR.GT.0) GO TO 105	UCA128
IF(IPRESS.LT.NCYC) GO TO 130	UCA129
145 WRITE(6,150) NCYC	UCA130
150 FORMAT(/,10X,"THE TOTAL NUMBER OF TIME SLUGS READ WAS",I5,////)	UCA131
GO TO 105	UCA132
999 CONTINUE	UCA133
END	UCA134

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE CALCAE

```

C *****
C
C SUBROUTINE CALCAE(PSOPOI,PM3SOI,OUT,IPRESS,NCT,NERROR,CURVE,
C   &MCRT)
C THIS SUBROUTINE DETERMINES THE FLOW REGIME, CALLS THE PROPER SUB-
C ROUTINES TO DETERMINE THE FLOW CONDITIONS AT STATIONS 1 & 3, AND
C CONTROLS ITERATION PROCEDURES.
C
C COMMON/BLOCK1/GP,GS,MP1,MWSP,TOSOPO,APIM3,MMIN,MMAK,MW,
C   &PCBIT
C COMMON/BLOCK2/MS1,MN3,PS1P1,PMOSQ,WSP,PM3SO
C REAL MS1,MP1,NCRT,MWSP,M,MX,MN3,MS1B,MR,MIN,MMAK
C LOGICAL NEW,CURVE,OUT
C
C W=SQRT(P*T0)/P*A=WM(G,M)
C   WM(G,M)=M*SQRT(G*(1.0+(G-1.0)*(M*M)*.50))
C TH P/PO FUNCTION.
C   PPO(G,M)=(1.0+(G-1.0)*(M*M)*.50)**(-G/(G-1.0))
C THE INVERSE OF THE P/PO FUNCTION
C   PM(G,P)=SQRT((PR*((1.0-G)/G)-1.0)*2.0/(G-1.0))
C P/P FOR A NORMAL SHOCK WAVE.
C   PYMX(G,M)=(2.0*G/(3+1.0))*(M*M)-(G-1.0)/(G+1.0)
C
C DATA ERRMS1,ERRORY,NITMAX/2*1.0E-4,35/
C DATA S2/"SP"/,SSR/"SSR"/,NR/"NR"/,APPR/"APPR"/
C MS1B IS THE LOWEST SECONDARY MACH NUMBER CONSIDERED IN A SEARCH FOR
C A SOLUTION.
C   NERROR=0 $ NCOUNT=1 $ DNS1B=.100 $ MS1B=.001
C THE MAXIMUM PS1P1 ALLOWED FOR CALCULATIONS TO PROCEED, PS1P1U,
C IS BASED ON A NORMAL SHOCK STANDING IN THE EXIT PLANE OF THE
C PRIMARY NOZZLE.
C   PS1P1U=PYMY(GP,MP1)
C   AS1P1=(1.0/APIM3)-1.0
C   CNST=SQRT(MWSP/TOSOPO)*AS1P1/WM(GP,MP1)
C IF THE REGIME IS SSR PS1P1>= 1.0 AND MS1= 1.0
C
C   REGIME=SSR
C   MS1=1.0
C   PS1P1=PPO(GS,1.0)*PSOPOI/PPO(GP,MP1)
C   IF(PS1P1.LT.1.0.AND.PSOPOI.LT.PCRIT) GO TO 20
C   IF(PS1P1.GT.1.0) GO TO 50
C THE PRESSURE RATIO LIES BETWEEN SR AND SSR REGIMES. PS1P1 = 1.0
C IS A GOOD APPROXIMATION
C   REGIME=APPR
C   PS1P1=1.0
C   PSISO=1.0*PPO(GP,MP1)/PSOPOI
C   MS1=PM(GS,PSISO)
C   GO TO 50
C IF SR MS1 MUST BE WINDOWED SUCH THAT MS1B < MS1 < MCRT
C 20 REGIME=SR $ NIT=1 $ NTYPE=1
C   MS1=MS1B
C 30 CALL FABRI(MS1,PS1P1,NERROR)
C   IF(NERROR.GT.0) GO TO 905
C   PS1PII=PSOPOI*PPO(GS,MS1)/PPO(GP,MP1)
C   IF((NIT*.EQ.1).AND.(PS1P1.GT.PS1PII)) GO TO 309
C   Y=(PS1P1-PS1PII)/PS1PII

```

# UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE) SUBROUTINE CALCAE

```

      IF((ABS(Y).GT.ERRORY).AND.(PS1P1.LE.PS1P11).AND.
& (ABS(MS1-MCRIT)/MCRIT.LT..0005)) GO TO 40
      IF((MS1+DMS1B).GT.MCRIT) DMS1B=(MCRIT-MS1)/2.0
      CALL ITER(MS1,DMS1B,ERRMS1,+1.0,Y,0.0,ERRORY,NIT,NTYPE,
& XNEG,YNEG,XPOS,YPOS,MSIGN1,MSIGN2)
      IF(NITMAX.LT.NIT.AND.NTYPE.NE.3) GO TO 40
      GO TO (30,30,50),NTYPE
C IF NO SOLUTION HAS BEEN FOUND MR WILL BE SEARCHED.
40 IF(OUT) WRITE(6,908)MS1,PS1P1,PS1P11
   GO TO 60
50 CALL OCV(MERROR)
   IF(MERROR.NE.0) GO TO 902
C IF THE VALUE OF PH3SO RETURNED BY OCV IS < PH3SOI THE
C SECONDARY MASS FLOWRATE IS DEPENDENT ON PH3SOI AND THE REGIME
C MUST BE MR.
      DELT=PH3SO-PH3SOI
      IF(REGIME.NE.MR.AND.PH3SO.GT.PH3SOI) GO TO 70
      IF(ABS(DELT/PH3SOI).LT.ERRMS1.AND.REGIME.EQ.MR.AND.
& DELT.LE.(0.0)) GO TO 70
C THE BACK PRESSURE IS TOO HIGH FOR THE SECONDARY TO BE CHOKED.
C MS1 IS LESS THAN THE BREAK-OFF VALUE AND THE REGIME IS MR. A
C VALUE OF MS1 PRODUCING A PH3SO=PH3SOI IN OCV IS SOUGHT.
60 IF(REGIME.NE.MR)MS1=.500
   REGIME=MR
   IF(NCOUNT.GT.25.OR.MS1.LT.MS1B.OR.MS1.GT..999) GO TO 904
   CALL ITMS1(MS1,PH3SO,PH3SOI,NCOUNT,MS1LO,MS1HI)
   PS1P1=PSOPOI*PPO(GS,MS1)/PPO(GP,MP1)
   GO TO 50
70 IF(PS1P1U.LT.PS1P1) GO TO 900
   WSP=CONST*PS1P1*WH(GS,MS1)
   IF(.NOT.OUT) GO TO 100
   IF(IPRESS.EQ.1) WRITE(6,80)
80 FORMAT(/,10X,"TIME SLUG DATA",/,3X,"SLUG",2X,"REGIME",4X,
& "PSOPOI",6X,"WSP",6X,"MS1",5X,"PS1P1",5X,"MH3",5X,
& "PHOSO",7X,"PH3SO",/)
   WRITE(6,90)IPRESS,REGIME,PSOPOI,WSP,MS1,PS1P1,MH3
& ,PHOSO,PH3SO
90 FORMAT(/,2X,I4,5X,A4,3X,F6.4,4X,F6.4,3(3X,F6.4),
& 3X,F7.4,3X,F8.4)
   WRITE(7,95) PS1P1
95 FORMAT(10F10.4)
100 CALL SUBUP(IPRESS,MCYC,PSOPOI,CURVE)
   RETURN
C ***** ERROR MESSAGES *****
900 WRITE(6,901) IPRESS,PS1P1,PS1P1U,MS1
901 FORMAT(/,"* * * * *",/,"ERROR IN CALCAE",/,"* * * * *",/,"TIME SLUG NO.",I4,5X,"PS1P1=",F8.4,5X,"PS1P1U=",F8.4,5X,"MS1=",F8.4)
   MERROR=1 & RETURN
902 WRITE(6,903) MS1,PS1P1
903 FORMAT(/,"* * * * *",/,"ERROR IN OCV",/,"* * * * *",/,"MS1=",F8.4,10X,"PS1P1=",F8.4)
   RETURN
904 WRITE(6,905) MS1,PH3SO,PH3SOI
905 FORMAT(/,"* * * * *",/,"ERROR IN CALCAE",/,"* * * * *",/,"NON-CONVERGENCE OF MS1 FOR THE INPUT PH3SO",/,"MS1=",F8.4,10X,"PH3SO=",F8.4,10X,"PH3SOI=",F8.4)
   MERROR=1 & RETURN

```

CAL061  
 CAL062  
 CAL063  
 CAL064  
 CAL065  
 CAL066  
 CAL067  
 CAL068  
 CAL069  
 CAL070  
 CAL071  
 CAL072  
 CAL073  
 CAL074  
 CAL075  
 CAL076  
 CAL077  
 CAL078  
 CAL079  
 CAL080  
 CAL081  
 CAL082  
 CAL083  
 CAL084  
 CAL085  
 CAL086  
 CAL087  
 CAL088  
 CAL089  
 CAL090  
 CAL091  
 CAL092  
 CAL093  
 CAL094  
 CAL095  
 CAL096  
 CAL097  
 CAL098  
 CAL099  
 CAL100  
 CAL101  
 CAL102  
 CAL103  
 CAL104  
 CAL105  
 CAL106  
 CAL107  
 CAL108  
 CAL109  
 CAL110  
 CAL111  
 CAL112  
 CAL113  
 CAL114  
 CAL115  
 CAL116  
 CAL117  
 CAL118

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE CALCAE

906 WRITE(6,907)	CAL118
907 FORMAT(/," * * * * * * * * * *",/,"ERROR IN FABRI",/," * * *	CAL119
5 * * * * * * * * *")	CAL120
NERROR=1     5     RETURN	CAL121
908 FORMAT(///,10X,"SOLUTION NOT FOUND IN SR BY FABRI WITH ITP",/,	CAL122
510X,"MS1=",F8.5,6X,"PS1P1=",F8.5,6X,"PS1P1I=",F8.5)	CAL123
909 WRITE(6,910)	CAL124
910 FORMAT(/,5X,"PSOP01 IS SO LOW THAT *S1<.001 IN SR.")	CAL125
NERROR=1     5     RETURN	CAL126
END	CAL127

# UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE) SUBROUTINE FABRI

```

C *****
C
C SUBROUTINE FABRI(MS1,PS1P1,NERROR)
C
C CONSTANT-AREA EJECTOR, FABRI CRITERION (FABRI) SUBROUTINE.
C
C 1-D EJECTOR ANALYSIS WITH SUPERSONIC PRIMARY (MP1>1) AND
C SUBSONIC SECONDARY (MS1<1) WHICH CHOKES IN THE EJECTOR
C SHROUD (MS2=1). THIS EJECTOR ANALYSIS IS BASED
C ON THE CONSTANT-AREA SHROUD EJECTOR ANALYSIS OF FABRI.
C REFERENCE: NACA TN 1410.
C
C COMMON/BLOCK1/GP,GS,MP1,MWSP,TSOP,AP1M3,MNIN,NEW,MHAX,
C SPCRT
C REAL M,MP1,MS1,MWSP,MNIN,MHAX,MP2
C LOGICAL NEW
C
C P/PO(G,M) FUNCTION.
C PPO(G,M)=(1+.5*(G-1.)*(M*M))*(-G/(G-1.))
C 1/A*(G,M) FUNCTION.
C AASH(G,M)=(1./M)*(((2./(G+1.))*(1.+0.5*(G-1.)*(M*M)))
C & **(.5*(G+1.)/(G-1.)))
C
C FABRI'S CRITERION APPLIES ONLY WHEN (MS1.LE.(1.0)) AND
C (PS1P1.LE.(1.0)).
C CALCULATE THE AREA RATIO FOR STREAM (P) AT STATION (2).
C AP2PS=(AASH(GP,MP1)/AP1M3)*(1.-(1.-AP1M3)/AASH(GS,MS1))
C CALCULATE MP2 AT STATION (2) WHERE MS2=1.0.
C CALL ASTAR(GP,AP2PS,MP2,MNIN,MHAX)
C CALCULATE STATIC PRESSURE RATIO PS1P1 BASED ON
C FABRI'S CRITERION.
C VD=(1.-AP1M3)*(((1.+GS*(MS1**2))-
C & (PPO(GS,1.0)/PPO(GS,MS1))*((1.+GS)/AASH(GS,MS1))))
C VN=(PPO(GP,MP2)/PPO(GP,MP1))*AP1M3*(AASH(GP,MP2)/
C & AASH(GP,MP1))*(1.+GP*(MP2**2))-AP1M3*(1.+GP*(MP1*MP1))
C PS1P1=VN/VD
C IF(PS1P1.GT.1.0.AND..NOT.NEW) WRITE(6,80)
C IF(PS1P1.LE.(0.0)) WRITE(6,60)
C IF(MP2.LT.MP1) WRITE(6,40)
C IF(PS1P1.LE.0.0.OR.MP2.LT.MP1) GO TO 90
C IF(PS1P1.GT.1.0.AND..NOT.NEW) GO TO 90
C RETURN
C
C ERROR MESSAGES.
C 40 FORMAT(/,5X,"...ERROR IN FABRI: (MP2.LT.MP1).",//)
C 60 FORMAT(/,5X,"...ERROR IN FABRI: (PS1P1.LT.(0.0)).",//)
C 80 FORMAT(/,5X,"...ERROR IN FABRI: PS1P1> 1.0",//)
C SET ERROR FLAG.
C 90 NERROR=2
C RETURN
C END

```

FAB001  
 FAB002  
 FAB003  
 FAB004  
 FAB005  
 FAB006  
 FAB007  
 FAB008  
 FAB009  
 FAB010  
 FAB011  
 FAB012  
 FAB013  
 FAB014  
 FAB015  
 FAB016  
 FAB017  
 FAB018  
 FAB019  
 FAB020  
 FAB021  
 FAB022  
 FAB023  
 FAB024  
 FAB025  
 FAB026  
 FAB027  
 FAB028  
 FAB029  
 FAB030  
 FAB031  
 FAB032  
 FAB033  
 FAB034  
 FAB035  
 FAB036  
 FAB037  
 FAB038  
 FAB039  
 FAB040  
 FAB041  
 FAB042  
 FAB043  
 FAB044  
 FAB045  
 FAB046  
 FAB047  
 FAB048  
 FAB049  
 FAB050  
 FAB051

# UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE) SUBROUTINE OCV

```

C *****
C
C SUBROUTINE OCV(NERROR)
C
C CONSTANT AREA EJECTOR OVERALL CONTROL VOLUME ANALYSIS (OCV).
C 1-D ANALYSIS FROM INLET STATION, 1, TO EXIT STATION, 3.
C
C COMMON/BLOCK1/GP,GS,MP1,MWSP,TSOPO,AP1M3,MNIN,MEX,MNAX,
C &PCRT
C COMMON/BLOCK2/MS1,MN3,PS1P1,PMOSO,MSP,PM3SO
C REVL 1,MN1,MS1,MN3,MN3M,MN3P,MNIN,MWSP,MWMP,MSQD3M,MSQD3P
C &,MNAX,MR
C LOGICAL NEW
C MH(G,M)=M*SQRT(G*(1.0+0.5*(G-1.0)*(M**2)))
C PPO(G,M)=(1.0+0.5*(G-1.0)*(M**2))*(-G/(G-1.0))
C A FORM OF THE 1-D THRUST FUNCTION.
C T(G,M)=(1.0+G*(M**2))/(M*SQRT(1.0+0.5*(G-1.0)*(M**2)))
C REDEFINE MR LOCALLY.
C MR="MR"
C CALCULATE CONSTANTS.
C C0=SQRT(MWSP/TSOPO)
C EJECTOR MASS-FLOW RATIO
C MSP=PS1P1*((1.-AP1M3)/AP1M3)*C0*(MH(GS,MS1)/MH(GP,MP1))
C CPSP=(GS/GP)*((GP-1.)/(GS-1.))/MSP
C MIXED FLOW PROPERTIES
C MWMP=(1.+MSP)/(1.+(MSP/MWSP))
C GM=1./((1.-((GP-1.)/GP)*((1.+(MSP/MWSP))/(1.+CPSP*MSP))))
C CALCULATE THE MIXED-TO-PRIMARY STAGNATION TEMPERATURE RATIO.
C TMOPO=(1.+MSP*CPSP*TSOPO)/(1.+MSP*CPSP)
C CALCULATE SOME CONSTANTS.
C C1=SQRT((TSOPO/MWMP)*(GP/GS))
C C2=SQRT(TMOPO/MWMP*(GP/GM))
C SOLVING FOR MN3.
C MN3=(T(GP,MP1)+C1*MSP*T(GS,MS1))/((1.+MSP)*C2)
C TM3MIN=SQRT(2.*(GM+1.))
C IF(TM3.LT.TM3MIN) GO TO 20
C C3=(TM3**2-2.*GM)
C C4=((GM-1.)*.5)*(TM3**2)-GM*GM)
C C5=SQRT(C3-C4+4.*C4)
C MSQD3M=(-C3-C5)/(2.*C4)
C MSQD3P=(-C3+C5)/(2.*C4)
C DETERMINE TWO POSSIBLE MIXED-FLOW MACH NO. SOLUTIONS.
C IF(MSQD3M.GE.(0.0)) MN3M=SQRT(MSQD3M)
C IF(MSQD3P.GE.(0.0)) MN3P=SQRT(MSQD3P)
C USE ONLY SUBSONIC RESULT AT (3).
C MN3=MN3P
C CALCULATE STATIC PRESSURE RATIO, PM3P1, AT (3).
C C6=SQRT(TMOPO/MWMP)
C PM3P1=C6*AP1M3*(1.+MSP)*(MH(GP,MP1)/MH(GM,MN3))
C CALCULATE OTHER STATIC AND STAGNATION PRESSURE RATIOS.
C PM3SO=(PPO(GS,MS1))*PM3P1/PS1P1
C PMOSO=PM3SO/PPO(GM,MN3)
C RETURN
C ERROR MESSAGES.
20 WRITE(6,30)
30 FORMAT(/,57,"...ERROR IN OCV: NO SOLUTION.",/)
NERROR=1
RETURN
END

```

OCV001  
 OCV002  
 OCV003  
 OCV004  
 OCV005  
 OCV006  
 OCV007  
 OCV008  
 OCV009  
 OCV010  
 OCV011  
 OCV012  
 OCV013  
 OCV014  
 OCV015  
 OCV016  
 OCV017  
 OCV018  
 OCV019  
 OCV020  
 OCV021  
 OCV022  
 OCV023  
 OCV024  
 OCV025  
 OCV026  
 OCV027  
 OCV028  
 OCV029  
 OCV030  
 OCV031  
 OCV032  
 OCV033  
 OCV034  
 OCV035  
 OCV036  
 OCV037  
 OCV038  
 OCV039  
 OCV040  
 OCV041  
 OCV042  
 OCV043  
 OCV044  
 OCV045  
 OCV046  
 OCV047  
 OCV048  
 OCV049  
 OCV050  
 OCV051  
 OCV052  
 OCV053  
 OCV054  
 OCV055  
 OCV056  
 OCV057  
 OCV058  
 OCV059  
 OCV060

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE PRATIO

C	*****	PRA001
C	SUBROUTINE PRATIO(AMP,PAVG,NCYC,PSOPOI,IPRESS,CURVE)	PRA002
C	THIS SUBROUTINE INITIALIZES THE INPUT STAGNATION PRESSURE RATIO,	PRA003
C	PSOPOI, FOR EACH TIME SLUG.	PRA004
C	COMMON/BLOCK2/MS1,MM3,PS1P1,PMOSO,WSP,PMISO	PRA005
	COMMON/BLOCK3/MS1,SPMOSO,SMH3,SPSOPO,SPS1P1,SWSP	PRA006
	LOGICAL CURVE	PRA007
	PI=3.141593	PRA008
	IF(CURVE) GO TO 80	PRA009
	READ(5,50) PSOPOI	PRA010
	IF(EOF(5)) 70,60	PRA011
50	FORMAT(F10.4)	PRA012
60	IPRESS=IPRESS+1	PRA013
	NCYC=IPRESS+1	PRA014
	RETURN	PRA015
70	NCYC=IPRESS	PRA016
	CALL SUBUP(IPRESS,NCYC,PSOPOI,CURVE)	PRA017
	RETURN	PRA018
80	IPRESS=IPRESS+1	PRA019
	PRESS=FLOAT(IPRESS)	PRA020
	CYC=FLOAT(NCYC)	PRA021
	PSOPOI=PAVG*(1.0+AMP*SIN(2.0*PI*PRESS/CYC))	PRA022
	RETURN	PRA023
	END	PRA024
		PRA025
		PRA026
		PRA027

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE CRITM

```

C *****
C SUBROUTINE CRITM(MCRIT)
C THIS SUBROUTINE IS USED TO FIND THE SECONDARY MACH NUMBER, MS1,
C AT WHICH PS1P1 = 1.0 IS ENCOUNTERED IN THE SR SOLUTION.
C
COMMON/BLOCK1/GP,GS,MP1,MWSP,TSCPO,AP1M3,MNIN,NEW,MNAX,
&PCRIT
REAL MP1,MCRIT,MWSP,MNIN,MNAX,M
LOGICAL NEW
M=.001
DM=.010
NTYPE=1
DO 10 I=1,300
  MNIN=MP1
  CALL PABRI(M,PS1P1,NEROR)
  IF(PS1P1.GT.1.0) GO TO 9
  IF(M.GE.(1.0)) GO TO 11
  OLDM=M
  GO TO 10
9  IF(NTYPE.EQ.2) GO TO 11
  DM=.00005
  M=OLDM
  NTYPE=2
10  M=M+DM
11  MCRIT=(M+OLDM)/2.0
  IF(MCRIT.GE.(1.0)) MNIN=MP1
  RETURN
END

```

CRH001  
CRH002  
CRH003  
CRH004  
CRH005  
CRH006  
CRH007  
CRH008  
CRH009  
CRH010  
CRH011  
CRH012  
CRH013  
CRH014  
CRH015  
CRH016  
CRH017  
CRH018  
CRH019  
CRH020  
CRH021  
CRH022  
CRH023  
CRH024  
CRH025  
CRH026  
CRH027  
CRH028  
CRH029  
CRH030

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE ASTAR

C *****	AST001
C	AST002
C	AST003
SUBROUTINE ASTAR(G,ARATIO,MP2,MMIN,MMAX)	AST004
C THIS SUBROUTINE SOLVES FOR MP2 GIVEN AP2/AP* FROM FABRI.	AST005
REAL MP2,MHI,MHIN,M,MLO,MMAX	AST006
C THE A/A* FUNCTION	AST007
AASH(G,M)=(1.0/M)*(2.0*(1.0+.5*(G-1.0)*(M*M))/(G+1.0))	AST008
&*((G+1.0)/(2.0*(G-1.0)))	AST009
C MAKE SURE THAT MMAX IS BIG ENOUGH FOR THE DATA SET INPUT.	AST010
MHI=MMAX	AST011
MLO=MMIN	AST012
NIT=1	AST013
10 AHI=AASH(G,MHI)	AST014
ALO=AASH(G,MLO)	AST015
MP2=MLO+(ARATIO-ALO)*(MHI-MLO)/(AHI-ALO)	AST016
IF(NIT.GT.30) RETURN	AST017
DIFF=ARATIO-AASH(G,MP2)	AST018
IF(ABS(DIFF)/ARATIO.LE..00001) RETURN	AST019
IF(DIFF.GT.0.0) GO TO 20	AST020
MHI=MP2	AST021
GO TO 30	AST022
20 MLO=MP2	AST023
30 NIT=NIT+1	AST024
GO TO 10	AST025
END	AST026

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE ITER

C *****	ITR001
C	ITR002
C	ITR003
C SUBROUTINE ITER(X,DX,ERRORX,SIGN,Y,YGIVEN,ERRORY,MIT,NTYPE,	ITR004
C &XNEG,YNEG,XPOS,YPOS,MSIGN1,MSIGN2)	ITR005
C SUBROUTINE PERFORMS AN ITERATION TO FIND X SUCH THAT THE	ITR006
C ABSOLUTE VALUE OF (Y-YGIVEN) IS .LE. TO ERRORY OR THE	ITR007
C ABSOLUTE VALUE OF (X(I+1)-X(I)) IS .LE. TO ERRORX.	ITR008
C VARIABLES:	ITR009
C X = INDEPENDENT VARIABLE	ITR010
C DX = INCREMENT IN INDEPENDENT VARIABLE	ITR011
C ERRORX = MAXIMUM VALUE OF ABS(X(I+1)-X(I)) FOR SOLN	ITR012
C SIGN = +1.0 OR -1.0, +/- INCREMENTING FROM INITIAL X	ITR013
C Y = DEPENDENT VARIABLE	ITR014
C ERRORY = MAXIMUM VALUE OF ABS(Y-YGIVEN)	ITR015
C YGIVEN = GIVEN VALUE OF DEPENDENT VARIABLE	ITR016
C MIT = INCREMENT NUMBER	ITR017
C NTYPE = 1--INCREMENT, 2--INTERPOLATION, 3--SOLUTION	ITR018
C	ITR019
DY=Y-YGIVEN	ITR020
IF((ABS(DY)-ERRORY).LE.0.0) GO TO 90	ITR021
IF(DY.GT.0.0) GO TO 20	ITR022
MSIGN2=-1	ITR023
XNEG=X	ITR024
YNEG=Y	ITR025
GO TO 40	ITR026
20 MSIGN2=+1	ITR027
XPOS=X	ITR028
YPOS=Y	ITR029
40 IF(NTYPE.EQ.2) GO TO 80	ITR030
50 IF((MIT-1).LE.0) GO TO 60	ITR031
MSIGN=MSIGN1*MSIGN2	ITR032
IF(MSIGN.LE.0) GO TO 80	ITR033
60 MSIGN1=MSIGN2	ITR034
MIT=MIT+1	ITR035
C INCREMENT TO FIND SOLUTION INTERVAL	ITR036
X=X+SIGN*DX	ITR037
GO TO 100	ITR038
C INTERPOLATION FOR SOLUTION	ITR039
80 NTYPE=2	ITR040
MIT=MIT+1	ITR041
XSAVE=X	ITR042
RATIO=(XPOS-XNEG)/(YPOS-YNEG)	ITR043
X=XNEG+RATIO*(YGIVEN-YNEG)	ITR044
IF(ABS(X-XSAVE) - ERRORX) 90,90,100	ITR045
90 NTYPE=3	ITR046
100 RETURN	ITR047
END	ITR048

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE ITMS1

C *****	IMS001
C	IMS002
C	IMS003
C SUBROUTINE ITMS1 (MS1,PH3SO,PH3SOI,NCOUNT,MS1LO,MS1HI)	IMS004
C	IMS005
C THIS SUBROUTINE SEARCHES FOR AN MS1 MEETING THE EXIT PLANE	IMS006
C PRESSURE CONDITION IN CONJUNCTION WITH OCV. REGANE=MR.	IMS007
C	IMS008
REAL MS1,MS1LO,MS1HI	IMS009
IF(NCOUNT.GT.1) GO TO 20	IMS010
MS1=.500	IMS011
MS1LO=0.0	IMS012
MS1HI=1.00	IMS013
NCOUNT=2	IMS014
RETURN	IMS015
C INCREASING MS1 DECREASES PH3SO SO:	IMS016
20 IF(PH3SO.GT.PH3SOI) GO TO 40	IMS017
MS1HI=MS1	IMS018
GO TO 60	IMS019
40 MS1LO=MS1	IMS020
60 MS1=(MS1HI+MS1LO)/2.0	IMS021
NCOUNT=NCOUNT+1	IMS022
RETURN	IMS023
END	IMS024

UNSTEADY CONSTANT AREA EJECTOR PROGRAM (UCAE)  
SUBROUTINE SUMUP

```

C *****
C
C
C      SUBROUTINE SUMUP(IPRESS,NCYC,PSOPOI,CURVE)
C      THIS SUBROUTINE CALCULATES THE MEAN VALUES OF MS1, PS1P1, WSP,
C      PHOSO, PSOPO, AND MM3. IF A DATA FILE IS TO BE READ IT SHOULD
C      CONTAIN AN INTEGER NUMBER OF PRESSURE CYCLES.
C
      COMMON/BLOCK2/MS1,MM3,PS1P1,PHOSO,WSP,PM3SO
      COMMON/BLOCK3/MS1,SPHOSO,MM3,SPSOPO,SPS1P1,SWSP
      REAL MS1,MM3
      LOGICAL CURVE
      IF(IPRESS.GT.1) GO TO 10
      MS1=0.0
      SPMOSO=0.0
      SMM3=0.0
      SPSOPO=0.0
      SPS1P1=0.0
      SWSP=0.0
10  IF(NCYC.EQ.IPRESS.AND..NOT.CURVE) GO TO 20
      MS1=MS1+MS1
      SMM3=MM3+SMM3
      SPSOPO=PSOPOI+SPSOPO
      SPS1P1=PS1P1+SPS1P1
      SPMOSO=PHOSO+SPHOSO
      SWSP=WSP+SWSP
      IF(IPRESS.NE.NCYC) RETURN
20  TOT=FLOAT(NCYC)
      MS1=MS1/TOT
      SMM3=MM3/TOT
      SPSOPO=SPSOPO/TOT
      SPS1P1=SPS1P1/TOT
      SPMOSO=SPHOSO/TOT
      SWSP=SWSP/TOT
      WRITE(6,30) MS1,SMM3,SPSOPO,SPS1P1,SPMOSO,SWSP
30  FORMAT(///,10X,"THE MEAN VALUES OVER A PRESSURE CYCLE ARE:",//,
& 10X,"MS1=",F10.4,10X,"MM3=",F9.4,11X,"PSOPO=",F7.4,///,10X,
& "PS1P1=",F8.4,10X,"PHOSO=",F8.4,10X,"WSP=",F8.4)
      RETURN
      END

```

SUM001  
SUM002  
SUM003  
SUM004  
SUM005  
SUM006  
SUM007  
SUM008  
SUM009  
SUM010  
SUM011  
SUM012  
SUM013  
SUM014  
SUM015  
SUM016  
SUM017  
SUM018  
SUM019  
SUM020  
SUM021  
SUM022  
SUM023  
SUM024  
SUM025  
SUM026  
SUM027  
SUM028  
SUM029  
SUM030  
SUM031  
SUM032  
SUM033  
SUM034  
SUM035  
SUM036  
SUM037  
SUM038  
SUM039  
SUM040

## A.2 SAMPLE PROGRAM INPUT AND OUTPUT

THE INPUT IS:

SIUCAE MP1=2.0,AP1M3=.333,MMAX=3.3,PH3SOI=2.345

THE OUTPUT IS:

INPUT DATA FOR CASE NO. 1

GS= 1.4000 GP= 1.4000 MWSP= 1.0000

PSOPO= 1.0000 AP1M3= .3330 MP1= 2.0000

PH3SOI= 2.3400

FOR THIS CASE, MCRIT= .8014 PCRIT= .1951

FOR THE SINUSOIDAL PRESSURE RATIO CURVE:

AMP= .100 PAVG= .1000 WCYC= 10 TIME SLUGS/CYCLE

SLUG	TIME SLUG DATA REGIME	PSOPO	WSP	MS1	PS1P1	MM3	PMOSO	PM3SO
1	SR	.1059	.2465	.4487	.7215	.5435	2.9384	2.4036
2	MR	.1095	.2577	.4551	.7434	.5446	2.8627	2.3398
3	MR	.1095	.2577	.4551	.7434	.5446	2.8627	2.3398
4	SR	.1059	.2465	.4487	.7215	.5435	2.9384	2.4036
5	SR	.1000	.2205	.4186	.6935	.5362	3.0744	2.5280
6	SR	.0941	.1946	.3867	.6643	.5287	3.2275	2.6679
7	SR	.0905	.1786	.3659	.6454	.5240	3.3328	2.7640
8	SR	.0905	.1786	.3659	.6454	.5240	3.3328	2.7640
9	SR	.0941	.1946	.3867	.6643	.5287	3.2275	2.6679
10	SR	.1000	.2205	.4186	.6935	.5362	3.0744	2.5280

THE MEAN VALUES OVER A PRESSURE CYCLE ARE:

MS1= .4150 MM3= .5354 PSOPO= .1000

PS1P1= .6936 PMOSO= 3.0872 WSP= .2196

THE TOTAL NUMBER OF TIME SLUGS READ WAS 10

## APPENDIX B

The initial phases of this research effort were concerned with the development of a large-scale, cold-flow, air fluidic oscillator to provide a periodic ejector driver flow and an investigation of the potential use of fluidic devices to enhance mixing between multiple supersonic streams.

## B.1 WATER TABLE EXPERIMENTS

The preliminary stages of this investigation were based on the hydraulic analogy and were conducted entirely on the water table. With this approach, simple and inexpensive experimental models could be rapidly fabricated which would provide a qualitative insight into the factors influencing the flow.

The use of the hydraulic analogy is generally accepted for modeling one-dimensional or plane two-dimensional, compressible flow; however, the analogy for unsteady, compressible flow modeling is not as well understood or accepted. Loh [40] derives the constitutive equations governing one-dimensional channel flow of a liquid and makes a comparison with the corresponding equations governing unsteady, compressible, isentropic flow. He concluded that qualitatively the analogy exists although the relationships between the two flows are considerably more complex.

All preliminary water table experimentation was done with styrofoam models. These models were cut with an electrically heated nichrome wire from four inch thick styrofoam blocks. To improve motion pictures of the

flow, a black polymer film was bonded to the styrofoam blocks prior to cutting so that the upper surface of all models would be highly visible against the white bedplate of the water table. The styrofoam models were mounted on a wooden bedplate with specially fabricated spiked clamps. The bedplate was clamped in position on the water table surface; gates and ports on the bedplate controlled the flow of water to the oscillator models.

Three basic fluidic oscillator geometries were investigated and are shown in Figs. B.1-1, B.1-2, and B.1-3. The principles of operation of the single-jet oscillator are discussed fully in Section 3.1; in a similar fashion, the balance-ended oscillator exploits the bistability of a jet impinging on a knife-edge. The middle jet of the three-jet interleaved oscillator is steady and is supplied through a port on the surface of the water table bedplate. These oscillator configurations were selected because of their simplicity and adaptability to the problems of interest. A flip-flop jet oscillator similar to Viets' configuration [30,31] was not considered because of the potential for high flow losses and its relative complexity.

The experimental procedure during the hydraulic analogy experiments was to gradually increase the height of the water in the large plenum upstream of the oscillator model being investigated until a desired level was reached and then the observations were made. The individual styrofoam pieces of the model could be repositioned easily so that the effects of the relative positions of the pieces could be investigated quickly.

The objectives of these preliminary hydraulic analogy experiments were:

1. To investigate the operational characteristics of these oscillator configurations;
2. To determine the factors influencing their behavior;
3. To determine if the pulsations of the three-jet oscillator enhanced mixing between interleaved supersonic streams; and
4. To examine a supersonic-subsonic ejector configuration on the water table which is driven by the single-jet oscillator in order to gain insight into the flow phenomena involved.

The single-jet oscillator configuration shown in Fig. B.1-1 performed very poorly. The motion of the jet was extremely irregular, moving only slightly left or right of the knife-edge and producing nearly negligible pressure pulses. The centerbody forming the feedback loop was recontoured as shown in Fig. B.1-4. The tendency of a jet to attach to a nearby wall, the *Coanda* effect, tends to pull the inlet jet away from the knife-edge so that it is directed into the feedback loop. The narrower feedback loop channel and the now vigorous action of the jet resulted in a strong pressure pulse moving through the feedback loop. The proximity of the feedback loop centerbody to the inlet jet also causes the inlet jet to flip well across the knife-edge into the resonance chamber when the feedback loop pulse reaches the inlet. This is because the surge of flow in the feedback loop can exit the loop only by deflecting the inlet jet toward the resonance chamber.

Figure B.1-5 is a photograph of a plexiglass model with the feedback loop centerbody moved away from the inlet jet. Figure B.1-6 is the same model with the centerbody moved slightly towards the jet. The jet action in the latter figure is much more pronounced and stable.

The balance-ended oscillator exhibited stability problems. If the stagnation height of the water in the plenum was gradually and carefully increased during start-up, the oscillator operated at about .44 Hz. A rapid start-up of the oscillator or a disturbance in the oscillator would result in the oscillator operating at approximately twice the previous frequency, about .90 Hz, and at half of the previous amplitude. Apparently the lack of surfaces near the jet leave it free to oscillate in higher frequency modes. If the resonance chambers are capable of sustaining these higher frequency modes, the oscillator will be somewhat unpredictable and unstable operation will be observed. Control vanes were positioned in the vicinity of the jet inlet as shown in Fig. B.1-7. The tendency for the jet to attach to these surfaces caused the jet to flip further to the left and right. This action prevented the jet from oscillating in higher frequency modes and increased the amplitude of the pulses.

Figure B.1-8 is the flow field produced by the three-jet oscillator. The large undulations in the steady jet at the center were absent when all three jets were steady.

The single-jet oscillator was also used to drive a supersonic-subsonic configuration during the hydraulic analogy experiments. Not much time was spent on this model due to leakage and secondary flow control problems.

The effects of the pulsed driver on the shock wave structure within the mixing duct and the rapid mixing of primary and secondary streams after the disintegration of the supersonic core, see Section 3.3.2, were observed.

A Super-8 color film detailing the above experiments is available upon request from Professor A. L. Addy.

The final series of hydraulic analogy experiments were performed with a plexiglass model of the single-jet oscillator; this is shown in Fig. B.1-9.<sup>†</sup> The plexiglass model has greater dimensional stability and control than the styrofoam model. The experiments with the styrofoam model gave only a crude picture of what factors affected oscillator performance and how. Features incorporated into the plexiglass model included (1) adjustable inlet and outlet jet widths, (2) adjustable inlet to knife-edge separation distance, and (3) a movable feedback loop centerbody. Leakage, which had been a problem with the styrofoam model, was prevented by using o-rings and a vacuum hold-down system.

Frequency, waveform, and amplitude characteristics of the single-jet oscillator model were accurately determined by videotaping, through the transparent glass and plexiglass walls of the water table and resonance chamber of the oscillator model, the passage of waves in the resonance chamber. A ruled scale and timer were located within the camera's view. Stop action, single-frame advance, and slow motion features of the video system aided accurate waveform and amplitude determination.

---

<sup>†</sup> This series of experiments and the design of the plexiglass oscillator model were performed by T. R. Stover [42], former graduate student.

A series of experiments were conducted with this oscillator model following a classical experiment sequence. The variables of interest were the ratio of the outlet jet to inlet jet width, the ratio of the inlet to knife-edge separation distance to the inlet jet width, and the ratio of the inlet jet width to the oscillator resonance chamber length. These ratios will be referred to as  $R_1$ ,  $R_2$ , and  $R_3$ , respectively.

Oscillator frequencies were found to be 12% less than what surface wave theory suggests. This is certainly due in part to the time required for the jet to flip across the knife-edge and then back again. Also, the ratio of the wave amplitude to mean water height was not negligible.

Amplitudes were found to rapidly increase with the ratio of knife-edge separation distance to inlet jet width,  $R_2$ , to some maximum value and then to gradually decrease as this ratio was further increased. The value of  $R_2$  at which the maximum amplitudes occurred was insensitive to  $R_1$  but increased slightly as  $R_3$  was decreased.

The ratio of the mean height of the water in the resonance chamber to the plenum chamber stagnation height was linearly proportional to  $R_1$ . Wave amplitudes were found to increase with  $R_1$  up to  $R_1 = 1.0$ . Lesser amplitudes were always observed when  $R_1$  was further increased to  $R_1 = 1.3$ . Generally amplitudes were found to increase with  $R_3$  too. These facts suggest that the maximum amplitudes are obtained at the maximum mass flowrate; i.e., when the inlet jet has the most energy as it flip-flops. Choking at the inlet appears to occur if  $R_1 > 1.0$ .

The waveform was not significantly altered by changes of any of these geometric ratios. The waveform rise times decreased slightly as the mass

flowrate was increased. A higher frequency beat was always noticed at the peak of each pulse. This was due to transverse oscillations of the jet while it resided in the resonance chamber. This is believed to be the cause of the high frequency beats seen in the air flow oscillator, see Fig. 3.3.2-29.

The results of these experiments were used to design the air flow oscillator. A value of  $R_1$  was selected that was sufficiently small to ensure, beyond any doubt, that the C-D primary flow nozzle at the ejector inlet was always choked but  $R_1$  was still sufficiently close to a value of 1.0 such that the maximum amplitude pressure pulses were approached;  $R_1 = 2/3$  was used. The oscillator design incorporated a movable knife-edge so that amplitudes could be adjusted. It was assumed that the mass flowrate through the oscillator would be large enough so that the optimum value of  $R_2$  would not be too large. A moderate value of  $R_2$  was used to determine the maximum knife-edge separation given the inlet jet width. Unless this value of  $R_2$  was far too small, the amplitude of the pulses obtained at the maximum knife-edge separation would be near the maximum obtainable for the previously selected value of  $R_1$ .

Details concerning the design and performance of the large-scale air flow oscillator can be found in Sections 3.1 and 3.3 of this report.

## B.2 AIR FLOW FLUIDIC OSCILLATOR EXPERIMENTS

A series of cold air flow experiments were run with the fluidic oscillator prior to all ejector experiments. Frequencies from 75 Hz to 250 Hz were examined; the highest frequency was limited by the minimum possible lengths of the feedback loop and resonance chamber.

The operating frequencies of the oscillator were about 25% less than the estimates made assuming pulses moved at the estimated sonic speed. By changing the resonance chamber length while keeping the feedback loop length constant and measuring the resulting frequencies, it was possible to estimate pulse propagation speeds. Propagation speeds were in excess of the sonic velocity as expected. Thus, it appears the time it takes the inlet jet to flip-flop is the cause for the low operating frequency limits.

The ratio of the resonance chamber to feedback loop lengths were varied over a wide range with no apparent effects other than frequency effects.

The results of these experiments were used to determine which operating frequencies and oscillator configurations would be used in the ejector experiments. The knife-edge setting was left at the maximum  $R_2$  or separation distance. Pressure pulses were considered to be sufficiently large and extending the knife could have caused vibration or leakage problems.



Figure B.1-1 The single-jet oscillator

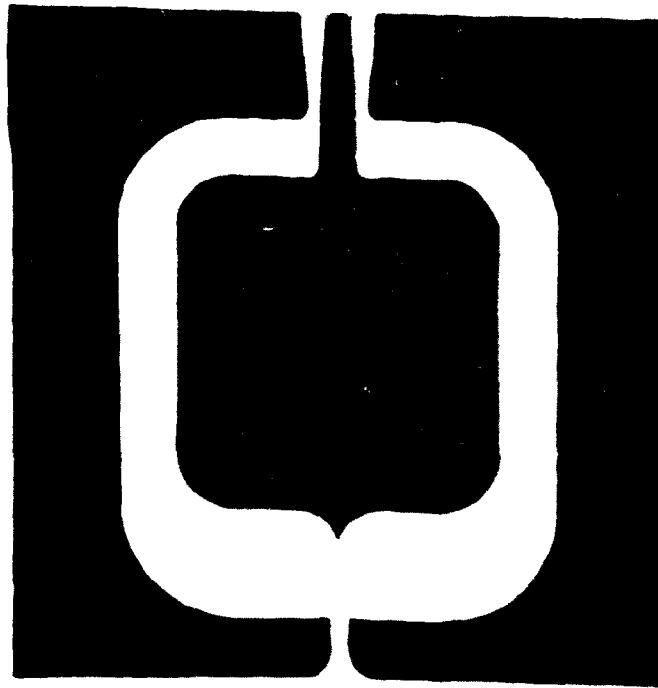


Figure B.1-2 The balance-ended oscillator

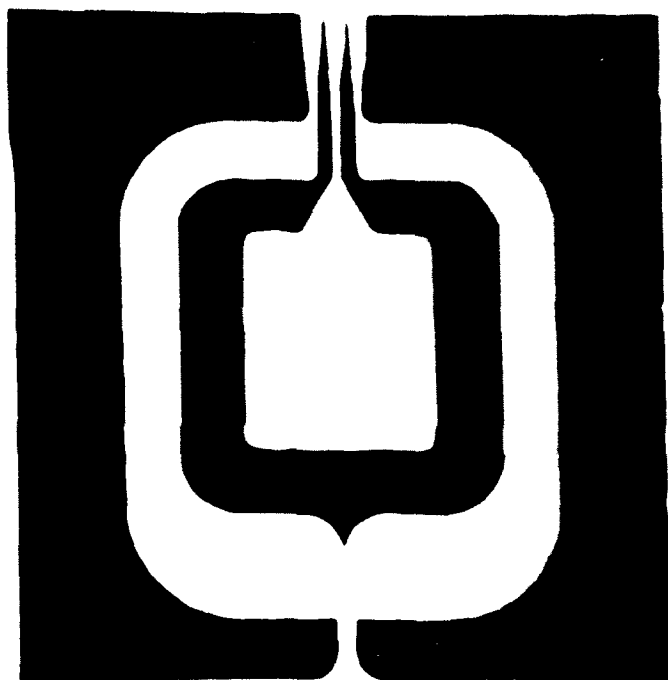


Figure B.1-3 The three-jet interleaved oscillator

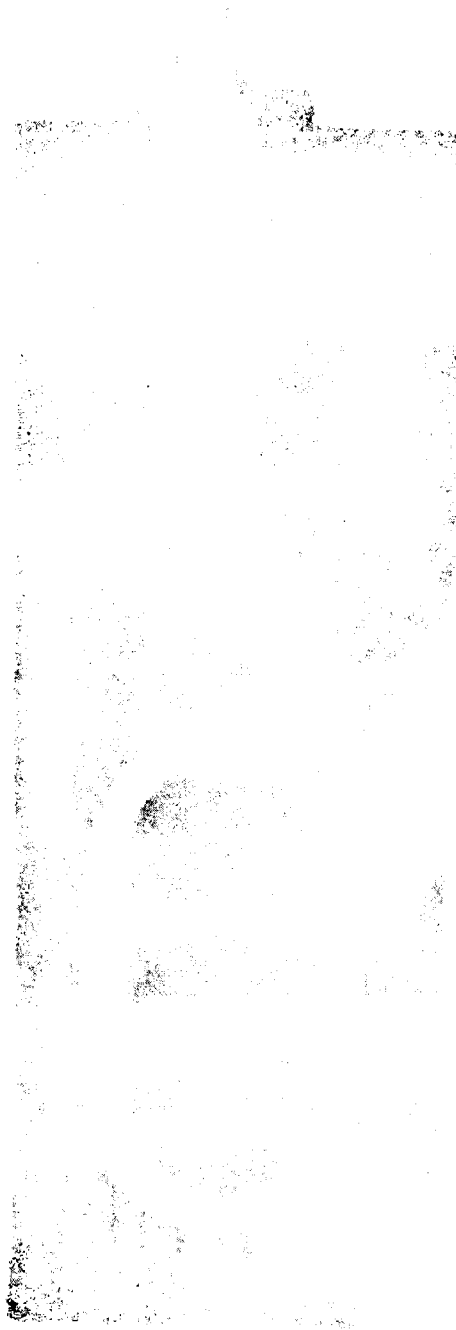


Figure B.1-4 The improved single-jet oscillator configuration

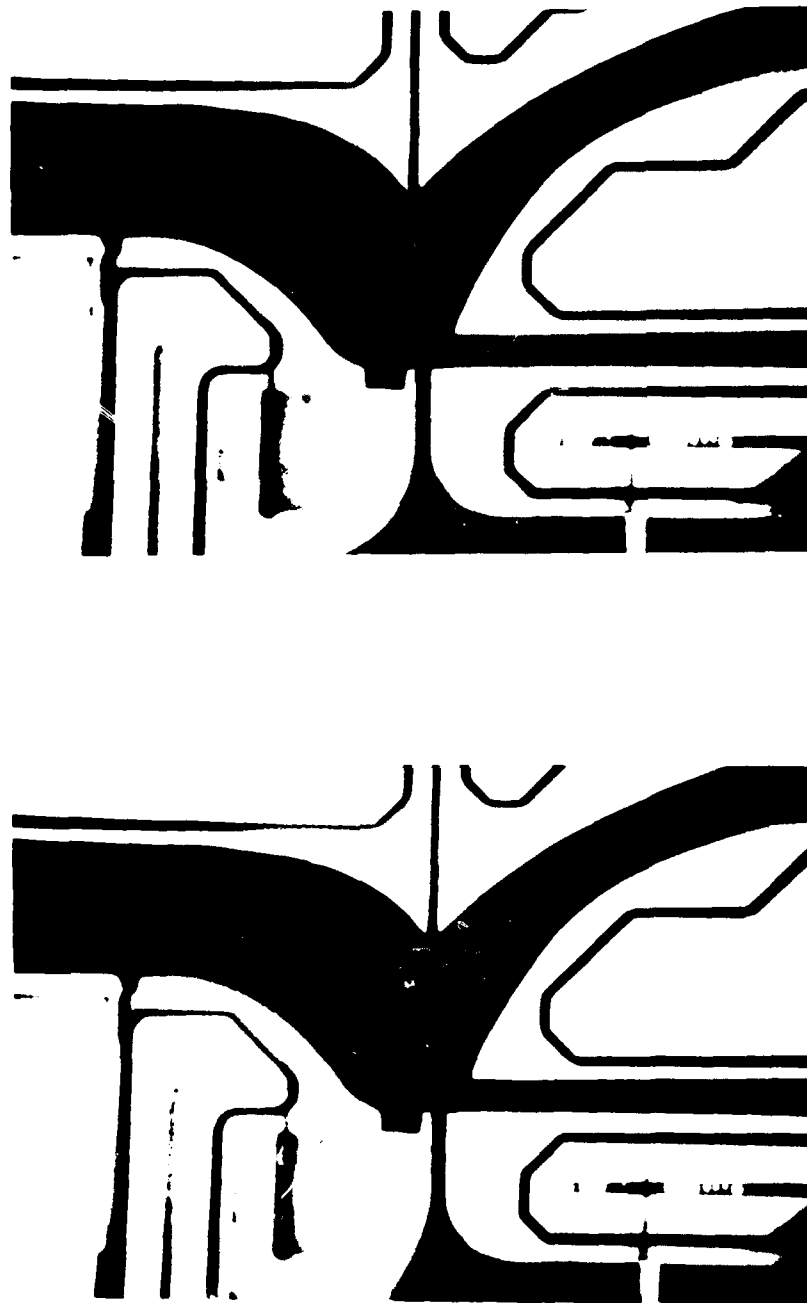


Figure B.1-5 Single-jet oscillator with centerbody moved away from inlet jet

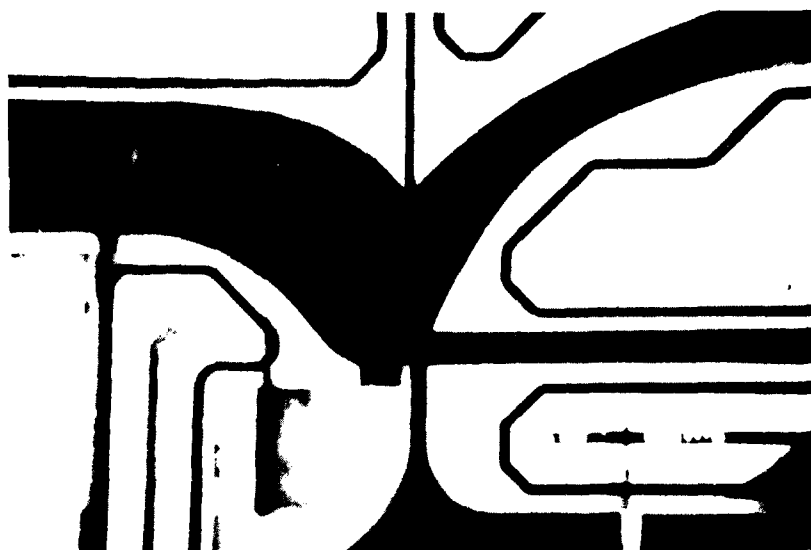
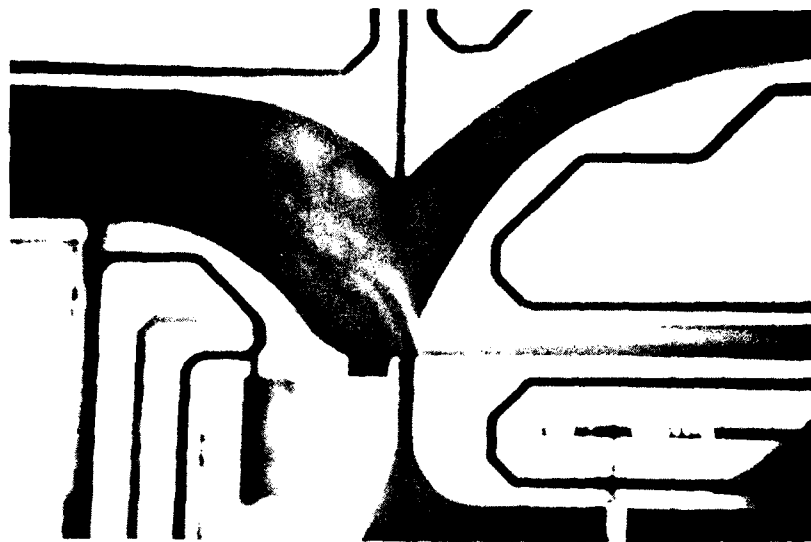


Figure B.1-6 Single-jet oscillator with centerbody in position for jet attachment

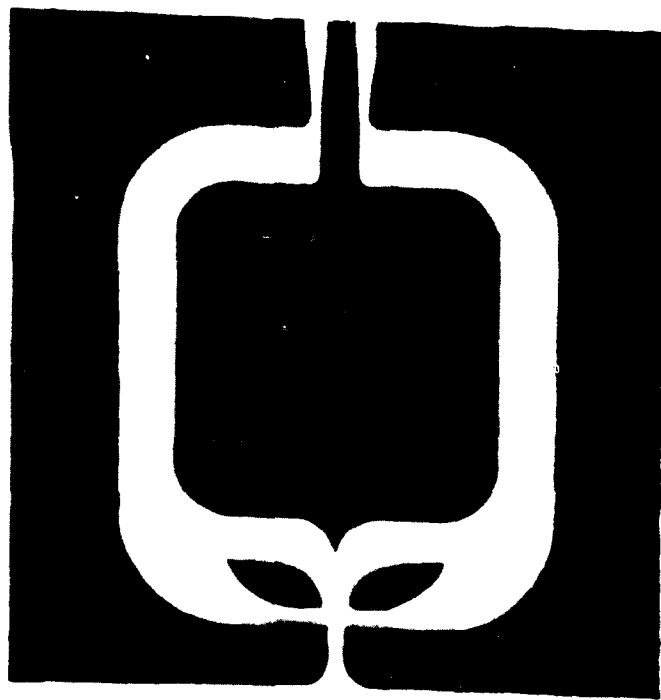


Figure B.1-7 Balance-ended oscillator with flow control vanes in position

Figure B.1-8 Three-jet interleaved oscillator flow field



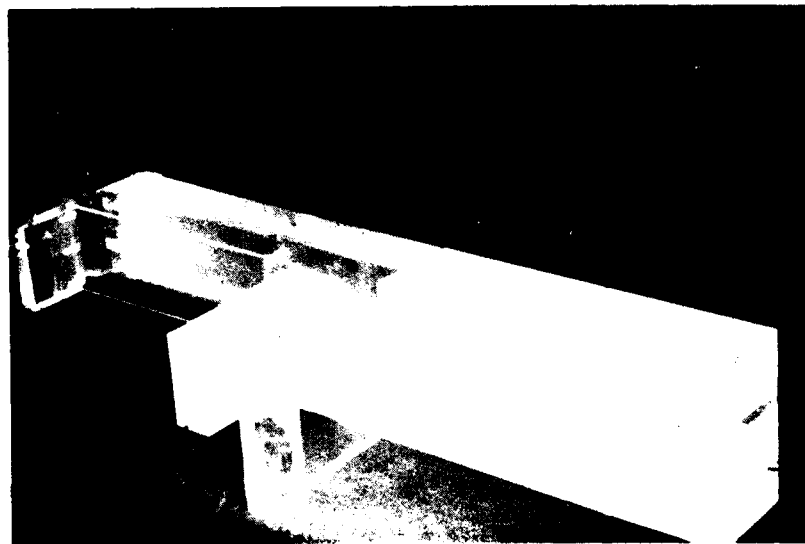
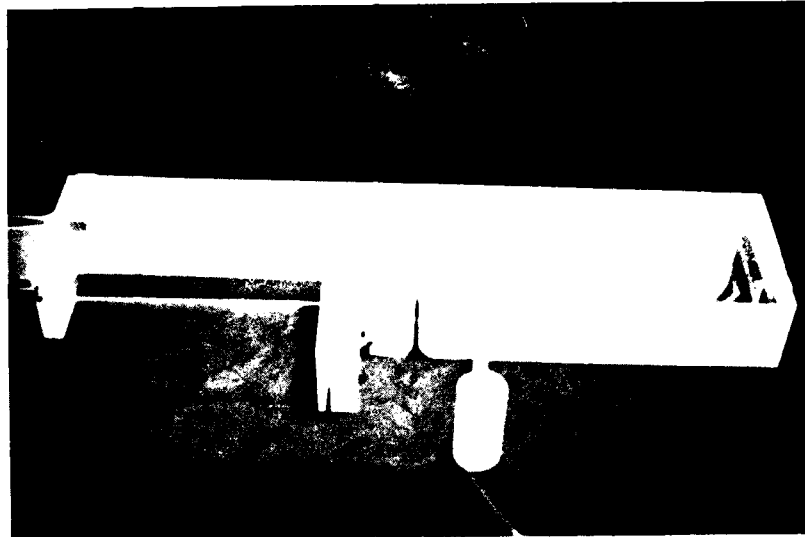


Figure B.1-9 Plexiglass model of the single-jet oscillator

## APPENDIX C

This appendix lists the faculty, graduate students, and support staff who participated on a part-time basis during the performance of this research grant.

FACULTY

A. L. Addy  
Principal Investigator  
Professor of Mechanical Engineering

GRADUATE STUDENTS

J. C. Dutton  
Ph.D. 1979  
Lawrence Livermore Laboratories

H. L. Petrie  
M.S. 1979  
Ph.D. Candidate

S. H. White  
M.S. 1978  
E. I. Du Pont De Nemours

T. R. Stover  
M.S. 1978  
Cummins Diesel

M. R. Sandberg  
M.S. 1977  
Petro-Marine, Inc.

V. Amatucci  
M.S. Candidate

D. Kuntz  
M.S. Candidate

SUPPORT STAFF

Karen Bryan  
Clerk-Stenographer III

PRECEDING PAGE BLANK - NOT FILMED

Allen F. Stephens  
Research Machine Shop Supervisor

Leroy Westendorf  
Instrument Maker